# Aging Aircraft Wiring Fault Detection Survey

Prepared for the

*Aviation Safety Program*
*Aircraft Aging & Durability Project*

as part of the

Wiring Fault Detection Challenge Problem

June 1, 2007
Version 1.0



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## Executive Summary

The accumulation of the information within this survey has occurred over a short period of time from many different sources.  Every effort was made to be as inclusive as possible and to honestly seek out technical gaps without any preconceived ideas.  That being said, it is our intention that the survey becomes a living document with additions and modifications made as new information becomes available.

During the process of collecting all of the information that is contained, it became readily apparent that the information required to understand wire chafing developments and requirements within the U.S is fragmented and the required data and models are at best difficult to obtain.  During the course of this survey we have highlighted five points:

**Point #1. Fault Physics Library** ***The broad failure categories cannot be easily mapped to the physics of degradation of wiring insulation and the corresponding electromagnetic characteristics. A physics-based fault library would be of great benefit to the community, especially one that contains the electromagnetic signatures of different types of dielectric damage.  Primary fault types that should be included are chaffing, partially connected and/or corroded connectors, and intermittent signal conduction associated with breaking or shorting events.***

In many communities the availability of datasets for which academics and their students can have access has resulted in a boon of research.  Current development efforts in the U.S. make the fault synthesis and data collection process inherent to funded development efforts.  This results in the data collected being considered as part of the inventor's intellectual property.  Although the taxpayers' money has been used to spur these developments, the data is rarely made available to anyone else (even government labs).  This then causes other funded inventors (typically with SBIR or STTR funding) to repeat the fault synthesis and data collection necessary to advance the field.  It would be of great benefit to the entire community if the government were to establish an electrical fault signature database that was open to all to pursue.

**Point #2. Quantitative Assessment** **-** ***There needs to be careful quantitative assessment of real-world effects that are typically ignored in the laboratory and appear randomly during field tests.  For example, the effects of varying humidity and vibration on the performance of wire fault detection schemes based upon electrical signal injection has not been substantially investigated in the literature.***

It is extremely rare that performance results obtained in the laboratory equal those obtained in the field and during operation.  Typically this is seen as necessary in the dirty real-world environment.  Unfortunately, much of the gross error could be mitigated before doing expensive field trials if the primary sources of error were identified and studied.  For the wire fault detection problem we know many of the sources of error which warrant further attention but which are typically ignored or vastly under-developed.  For example, we know that the effects of varying vibration, humidity and multi-wire geometry affect greatly the classical signal injection techniques.  With the appropriate experimental setup and with the proper mathematical framework these sources of errors can be modeled and mitigated.  Without doing this it is impossible to quantify how good is good enough when testing diagnosis and prognosis developments.

**Point #3. Testing & requirements guidance  - Every wire health management project, whether associated with a smaller academic effort, a small business innovative development, large industry/system integrator efforts or flight operations should be evaluated in the same way.  This should include a three prong effort utilizing simulation, theoretical characterization and laboratory data collection involving realistic environmental factors such as humidity and vibration.**

It is possible to categorize the testing and development cycles into three classes:

1. initial laboratory developments
2. fixed test-stand tests
3. flight tests

The first phase has the least uniformity amongst developments surveyed, is the least expensive to conduct, and should be but typically is not the most informative before performing more expensive tests.  The second phase typically involves testing on a grounded aircraft that is specifically made available for such purposes such as the FAA's testing facility.  The third phase is the most expensive but also the most revealing about the effects of real-world conditions such as humidity and vibration.  Typically the third phase is associated with either directed (or earmarked) funds or Phase II SBIRs (if government aircraft) and is the most expensive.  Effort is needed in helping to define the testing requirements and the specific implementation standards necessary for testing in the first phase that could reduce surprises learned in the later stages.

**Point #4. Understanding electromagnetics** ***Understanding how the electromagnetic wave propagation changes within wiring with damaged insulation is fundamental to developing signal injection and measuring devices for fault detection and prognosis.***

The leading wire chafing detection efforts in the United States have devoted minimal effort to simulating the best type of signal to inject even though the success of the technology development efforts depends upon understanding electromagnetic wave propagation.  Essentially the principle investigators that we have spoken with are interested in conducting these types of studies but have been unable to secure funding to do so.  Since most of the funding in wire fault detection comes in the form of SBIRs (or STTRs), the development cycle is fast paced and leaves little time (or money) for the research necessary to ensure that the development directions are optimized.

The FAA has also funded modeling efforts through the work of excited dielectrics [Van Alstine2005]. Unfortunately, the approach pursed was lacking in modeling all of the unknowns by reducing to just modeling capacitance and therefore was not continued.

### Point #5. Simulation, data collection, modeling & model inversion

***Critical analyses need to be comprised of three basic elements: 1. simulation, 2. data collection and 3. theoretical modeling and model inversion. Critical analyses must be model based. Small reflection signals buried inside of noisy time-domain data may be extremely useful if they can be pulled out. This process of signal extraction is referred to as model inversion. Without a comprehensive model, it is extremely difficult to analytically assess how well the inversion can characterize and classify wiring faults.***

Several papers by Lundstedt [Lundsted1997, Lundstedt1996 and Lundsted1994] have developed a rigorous approach to retrieving the spatially varying L, C, R and G parameters of a non-uniform transmission line. This work or ideas similar to it need to be explored further and incorporated into an inversion system that actively injects signals to both detect faults and monitor fault progression. Currently none of the development efforts that are focused upon developing hardware for wiring fault detection use any form of quantifiable parameter retrieval.

The five points raised by this survey are meant to highlight areas that we have concluded to be gaps in the nation's portfolio. Obviously the wire and connector fault detection and prognosis problem is difficult and each agency is doing the best that it can with the resources given. It is encouraging to see the level of open communication between the agencies that are engaged in fault detection development. The gaps presented in this survey are of a fundamental nature that if addressed, could have a positive impact on the entire community. The points raised are not without controversy. Fundamentally, open access to relevant data sets would prove fruitful in encouraging academia to wrestle with this challenging problem. There are aspects, especially electromagnetic modeling, which has a down side. In particular, electromagnetic simulations are computationally very expensive and are typically not representative of even clean laboratory conditions. Once known, this issue can be mitigated using *a three prong philosophy* behind every development effort:

1. Collect data in the laboratory using environmentally realistic conditions
2. Develop a thorough theoretical accounting for all aspects of the problem including undesirable noise sources while keeping in mind that model order reduction may be necessary in order to produce timely results.
3. Perform simulations that are modified to more accurately represent real-world conditions.

Thus this summary is advocating collecting realistic data, providing this data to the community, developing the appropriate theoretical approach, using simulations and data collection for development and eventually leading to requirements definition for all aspects of the wiring fault detection problem.

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# 1. Introduction

The problem of aging aircraft wiring received a great deal of attention in the late 1990s due to two tragic accidents: the July 1996 mid-air explosion of the Boeing 747 TWA Flight 800 and the crash of a Swissair MD-11 in Nova Scotia. The NTSB (National Transportation Safety Board) later determined the cause of the TWA 800 accident to have been a wiring failure that led to an ignition spark in the fuel tank. The Swissair disaster is believed to have been caused by electrical arcing originating from an in-flight entertainment cable. These disasters provided the initial impetus to begin reshaping commercial wiring policies. This resulted in the formation of the FAA’s (Federal Aviation Administration) ATSRAC (Aging Transport Systems Rulemaking Advisory Committee) as well as academic and small business funding opportunities from the FAA, NAVAIR (Naval Air Systems Command), NASA (National Aeronautics and Space Administration) and other agencies. This survey assesses the current state-of-the-art in wire fault detection resulting from developments over the last decade in academia, industry, and government laboratories. The result of this survey is an assessment of the gaps in the technical developments that have occurred and suggestions as to how these gaps might be addressed.

The programmatic considerations for this survey were to consider the long-term research challenges associated with aircraft wiring fault detection (diagnosis and prognosis) as pertains to future aircraft. The necessity of extending the definition of wiring to a greater system will also be shown, giving consideration to faulty connectors as an integral part. Conversely, arc fault interrupt (AFI) technology has matured beyond the phase of fundamental research and has not been included within this survey.

## 1.1. Outline

This survey will examine the current state-of-the-art for wiring fault detection as developed by academia, industry and national laboratories. This includes an overview of detection methods. Since this survey is also meant for future aircraft, we have included a section on methods for assessing fiber-optic cables. This is followed by the research and development efforts of small business, industry and national laboratories. The next section briefly covers current practices and discusses requirements. This is followed by a more detailed presentation of the mathematical physics behind modeling wire and optical faults. This leads to a discussion on simulation strategies and therefore we summarize current electromagnetic software packages and Bayesian model inversion. Finally we conclude with a gap assessment and specific points that might be addressed with additional research.

This survey focuses upon technologies for characterizing wiring fault degradation (before short or open state) based upon electrical (and optical) signal characteristics (e.g. electromagnetic waves). This survey does not focus upon arc fault interrupt technology both because it is maturing rapidly and also because in some sense, this is an after the fault technology and we are focused upon detection prior to full short circuits.

## 1.2. Motivation

Although the TWA 800 Boeing 747 and the Swissair MD-11 tragedies are cited as the impetus to research and development efforts in addressing aging wiring in aircraft, there have been a considerable number of incidents that have not resulted in crashes but have been attributed to electrical wiring failures. Avionics Magazine [AVMAG2003] reported that during the cruise phase of a flight a "smoke" event is more than twice as likely as an engine problem to cause an unscheduled landing, according to a study of service difficulty reports. In-flight electrical fires are indeed not rare events:

- According to Captain Jim Shaw, manager of the in-flight fire project for the United States Air Line Pilots Association (ALPA), there are on average three (3) fire and smoke events in jet transport aircraft each day in USA and Canada alone, and the vast majority are electrical [ASW2000].
- According to Air Safety Week, "aircraft are making emergency landings, suffering fire damage to the point of being written off etc, at the rate of more than one a month based on the experience of the past few months" [ASW2001].

Part of the problem stems from fleet operators continuing to rely upon older aircraft due to economic considerations. The result is that the average age of fleets (both commercial and military) is becoming older than the manufacturers expected serviceable life. This problem cannot be easily mitigated with an expensive replacement strategy because it is an average age issue and would require the replacement of too many aircraft. The military is also struggling with this issue and cannot obtain funds to simply rewire all aging aircraft, although some fighter aircraft are undergoing extensive rewiring for life extension by removing wiring insulated with Kapton (degrades with age and humidity).

## 1.3. Lessons Learned

The Coast Guard, NAVAIR, NASA and the FAA all have programs to assess the most prominent failures in electrical wiring. Although each agency has different aircraft, different maintenance practices, different data collection methods, and different operating environments, all of these agencies experience very similar wire aging issues. Figure 1 depicts data from Lee2000 detailing wiring faults found during routine maintenance and operations from 1980 to 1999. This figure shows that wire chafing composes approximately a third of all wiring faults. This number is actually under-representative due to the way in which maintenance personnel report failures. The chafing problem is even bigger when considering that the next category is unspecified short and the third largest category is broken wires, both of which could have come about due to chafing and bad maintenance practices.

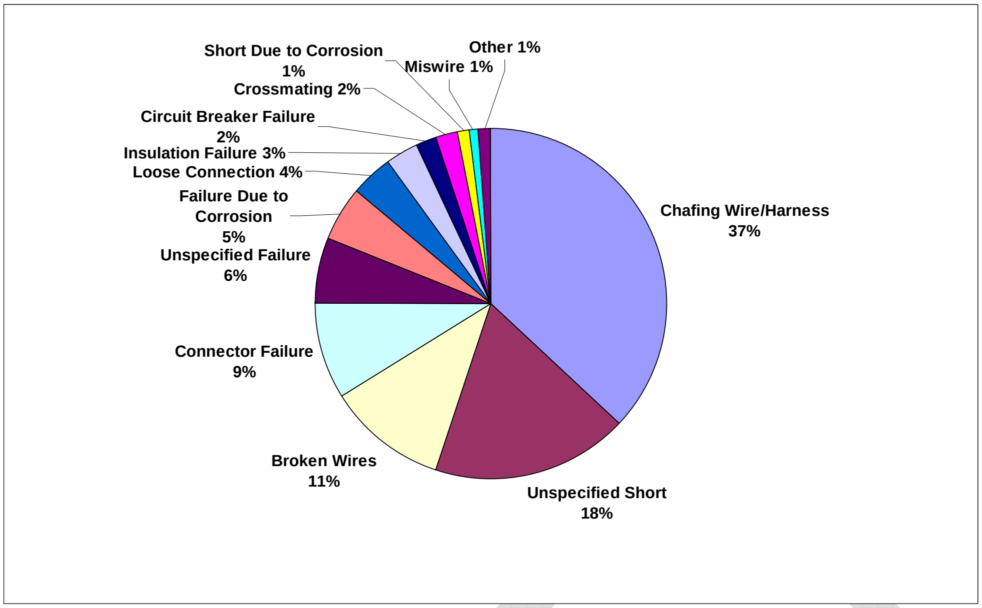


**Figure 1. U.S. Navy Wiring Systems Lessons Learned, David Lee & Pall Arnason, derived from Navy Safety Center Hazardous Incident data 1980 - 1999.**

The FAA ASTRAC committee reports [ASTRAC2000] similar, although more aggregated results as shown in Figure 2. This figure is a result of the FAA deconstructing six aircraft (DC-8, DC-9, DC-10, 727, 737, 747). As part of the teardown, the wiring harnesses were visually inspected and samples were taken to undergo laboratory tests. More than half of all of the wiring faults found were related to a breach in the insulation. Another 14% of these were cut or broken wires that may have arisen from chafing.

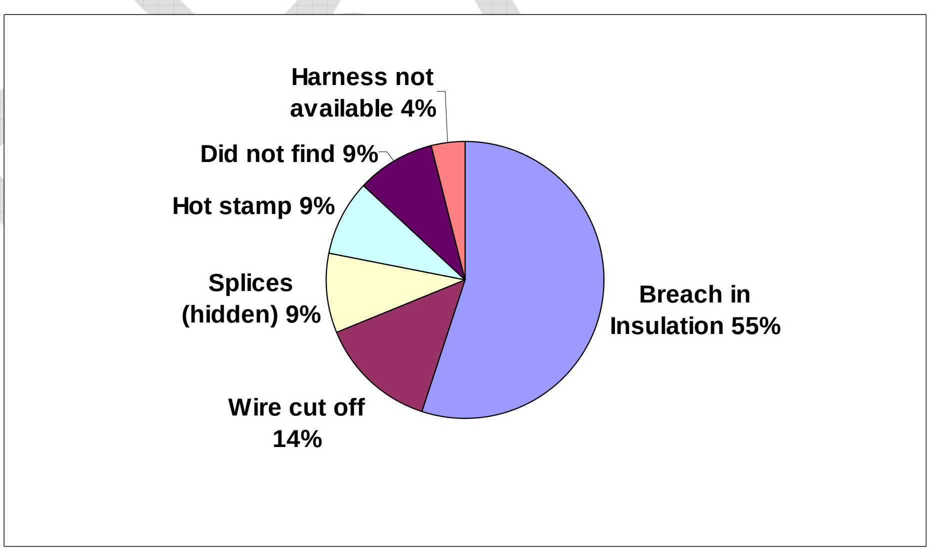


**Figure 2. FAA ATSRAC findings from examining 6 aircraft: DC-8, DC-9, DC-10, 727, 737, and a 747**

The FAA ATSRAC committee used the following fault categories during assessment:

- **Inadequate Repair:** An inadequate or inappropriate repair to *wire*.

- **Degraded Repair:** A deteriorated *wire* repair.
- **Heat Damage:** Heat Damaged *wire*.
- **Arcing:** Evidence of arcing from a *wire*.
- **Vibration Damage:** a.k.a *wire* chafing
- **Collateral Damage:** Indirect *wire* or *wire bundle* damage resulting from a traumatic event in the vicinity of that wire or bundle.
- **Cracked Insulation:** A breach or partial breach in the *wire* insulation resulting from excessive embrittlement of the insulation.
- **Nontraumatic Abrasion:** a.k.a *wire* chafing. Despite the redundancy with Vibration Damage, this category must remain in order to ensure compatibility (comparability) to ASTF categories.
- **Traumatic Damage:** Any damage to a *wire* or *wire bundle* resulting from sudden impact, excessive shear, excessive compression, excessive tension, or incision.
- **Broken Shield:** Severed or partially severed wire shielding.
- **Broken Conductor:** Severed or partially severed wire conductor.
- **Exposed Shield:** Exposed wire shield
- **Exposed Conductor:** Exposed wire conductor.
- **Fluid or Chemical Contamination:** Unexpected fluid or chemical contamination on *wire*.
- **Wire Corrosion:** Corrosion of *wire* conductor or chemically induced deterioration of *wire* insulation.
- **Other Wire Conditions:** Other *wire* condition not specifically mentioned above.

Although these categories as well as those from the Navy are helpful in determining the basic statistics of failure, it is impossible to assess cause and effect from these categories. Efforts are currently underway to refine these categories into finer subcategories. This will help with further statistical analyses but the root causes will still be difficult to determine. It is also difficult to understand how the failed wiring degrades with respect to time and how this degradation might appear to affect the electrical signals conducted by the wiring harnesses.

Figure 3 depicts wiring failure data collected by the Coast Guard. Note that in this case the data are different, whereby the majority of noted failures are due to connector failure. Since humidity tends to be high for the typical operating environment of the Coast Guard rescue helicopters, corrosion is a significant issue. The number of failures due to chafing is nearly equal.

We learned via private conversations with airline operators, FAA and Navy personnel that better maintenance training and better maintenance documentation would greatly help as a preventive measure towards wiring health. More than one anecdotal story has revealed that it is common for maintenance personnel to be the initiating cause for wiring chafing due, for example, to improper clamping of harnesses. Other stories included using wiring harnesses as ladders. Finally, improper practices such as pushing additional wires through a clamp during hasty maintenance cause chafing as well.

The majority of statistics collected to date are not associated with composite body aircraft. How the transition from aluminum to composite materials will affect future wiring is unknown. There are a number of possibilities. For example, one of the causes of wire chafing and/or breaking is from the main aircraft door slamming shut and pinching wiring either directly or through induced forces. These effects will be different for composite aircraft. Another issue has to do with electrical ground planes that are large in an aluminum aircraft and that are significantly different in composite aircraft.

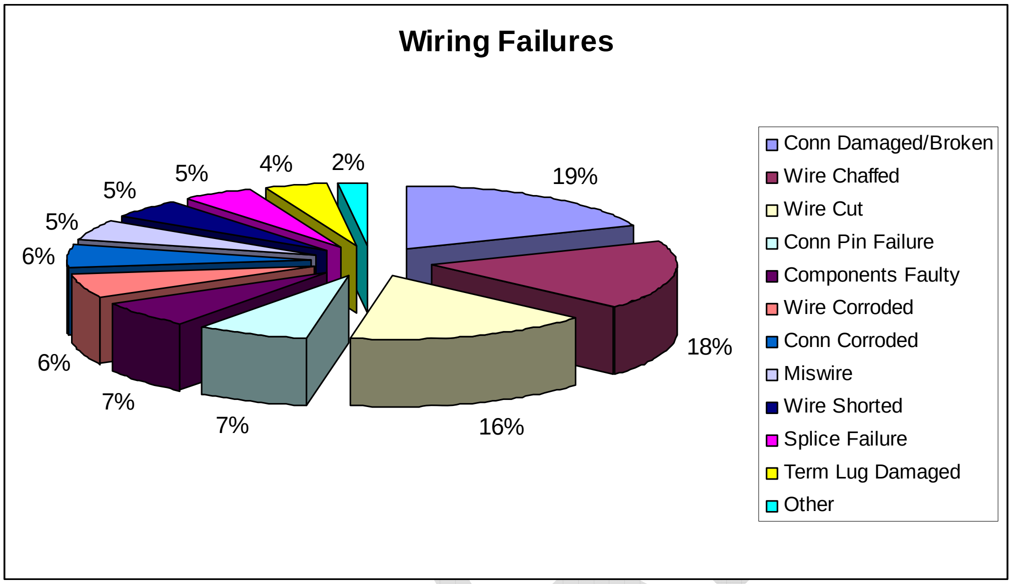


**Figure 3 Coast Guard wire failure data taken from "Statistical Analysis for Automated Wire Test Operations" by Keith Stevenson USCG and Michael Bequette (DIT-MCO Intl.).**

The capability of visual inspection of wiring to reveal electrical faults has been documented as only 25% effective [Teal2000]. Teal and Larsen [Teal2003] also note that: 90% of faults of a single type by kind and location were repeated aircraft to aircraft, 10% of fault types are seldom encountered and hard to detect, and 80% of faults are human induced. This leads to the first point of this survey:

**Point #1. Fault Physics Library** ***The broad failure categories cannot be easily mapped to the physics of degradation of wiring insulation and the corresponding electromagnetic characteristics. A physics-based fault library would be of great benefit to the community, especially one that contains the electromagnetic signatures of different types of dielectric damage. Primary fault types that should be included are chaffing, partially connected and/or corroded connectors, and intermittent signal conduction associated with breaking or shorting events.***

There are multiple meanings to "*physics-based*". Some investigators consider this to mean understanding the molecular basis of dielectric breakdown as a function of age and environment. This could for example mean understanding how micro-cracks are formed. A great deal of work in this area for Polyimide wire insulation occurred in the 1980's [Germeraad1982] long before the loss of life tragedies. While it is important to understand this type of age-based decomposition, in this report we have come to the conclusion that it is also important to understand the electromagnetic wave properties of wiring as the insulation becomes damaged, independent of whether the damage is caused by poor maintenance practices or age based chemical decomposition. The advantage of focusing upon electromagnetic signature approaches over insulation compound specific analyses is that the methods will be possible to implement for all aircraft and helicopters in the present and future rather than be tied to a particular type of wiring.

A signature based system holds the potential to be rapidly adapted to wiring harnesses that use a new type of insulation regardless of whether the fault initiates from human error or from chemical processes. Figure 4 was published in [Seher2001] and shows that three different types of insulation have been used in the last three decades. From the 1960s through the 1970s PVC and Nylon we used. Through the 1980s into the 1990s PI and more lately Teflon have been used. The likelihood that new wiring and insulation materials will be used in future aircraft is high since the industry is constantly striving to increase the efficiency and decrease the weight of their wiring systems.

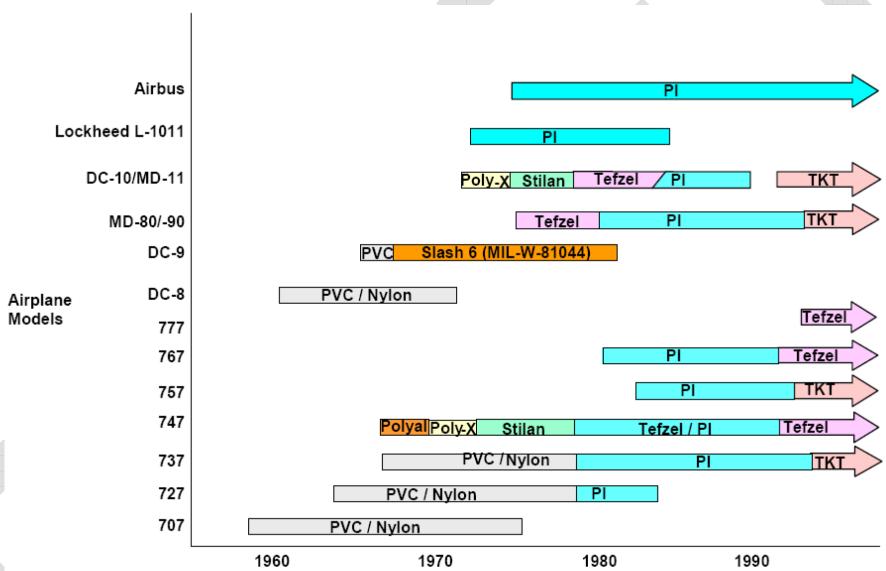


**Figure 4. Wire utilization as documented in [Seher2001]. Three major transitions in insulation type have occurred in the last three decades.**

# 2. Technology Assessments

## 2.1. Wire Fault Detection Methods

### 2.1.1. TDR

Time domain reflectometry – TDR consists of introducing a square wave pulse or step function on a wire for a few microseconds. Other waveforms such as Gaussian pulses are also used. Reflections are measured (picoseconds) from changes in power which indicate varying impedance along the wire and connectors. The distance to a short or open condition is determined via timing of the return of the reflection relative to the incident pulse, the speed of propagation and the length of the wire. The phase (or sign) of the reflection distinguishes between open and short conditions. Although TDR is very well established, the reflection results are very difficult to interpret. The Navy has funded work in using wavelets as a means to create a unique feature vector for TDR reflections [Hinders2006]. There are several well established manufacturers of TDR equipment that will be highlighted later in this report.

### 2.1.2. FDR

Frequency domain reflectometry [Furse2003] – Instead of using a fast rising DC pulse as does TDR, FDR sweeps through a range of frequencies to characterize the interference that occurs between the source and the reflections.

### 2.1.3. SWR

Standing Wave Reflectometry or Standing Wave Ratio (SWR) is the ratio of the amplitude of a partial standing wave at an antinode (maximum) to the amplitude at an adjacent node (minimum). The voltage component of a standing wave in a uniform transmission line consists of the forward wave (with amplitude $V_f$) superimposed on the reflected wave (with amplitude $V_r$).

Reflections occur as a result of discontinuities, such as an imperfection in an otherwise uniform transmission line, or when a transmission line is terminated with other than its characteristic impedance. SWR is typically used in testing of complex wiring harnesses at the end of production lines.

### 2.1.4. MCR

Multi-carrier Reflectometry [Naik2006] - Instead of stepping across discrete frequencies, all desired frequencies are mixed together into a periodic waveform. This is currently an academic approach.

### 2.1.5. Micro-radar

Lawrence Livermore National Laboratory (LLNL) has developed a hand-held micro-pulsed radar system [Azevedo1996]. The military objective is to be able to see through walls. Other applications have been suggested, including non-destructive testing and diagnosis with an implied potential for wiring diagnostics, although no specific results are known for this domain.

### 2.1.6. MET

Micro Energy Tool [Ballas2005] – A General Dynamics tool that produces low energy high voltage at a needle point probe. A technician moves the tip along the outside of a wire manually to find the location of the insulation flaw.

### 2.1.7. NDR

Noise Domain Reflectometry [Lo2005] – NDR is reflectometry that uses the native signals and measures associated reflections instead of injecting a known impulse. This approach has only appeared in academic papers.

### 2.1.8. STDR

Sequence Time Domain Reflectometry – STDR uses a pseudo-random noise generator to produce a sequence of bits, for example +1v and -1v to generate miniature impulses. The low autocorrelation of the sequence keys results in a signal that can be used as part of a correlation analysis to align reflections. This method has been replaced with SSTDR.

### 2.1.9. SSTDR

Spread Spectrum Time Domain Reflectometry [Smith2005, Taylor1996] - SSTDR is STDR in which the pseudo-random noise sequence is used to modulate the phase of a sinusoid. This is essentially Binary Phase Shift Keying in which a +1V bit results in zero phase and a -1V bit results in 180 degree phase shift. This modulated sinusoid can then be superimposed upon native signals such as the +/- 5V signals found on a 1553 communication bus. There are two small businesses that are both funded through SBIR (Small Business Innovative Research) Phase II grants in the process of developing SSTDR technologies. NAVAIR is funding Intelligent Automation Inc. and the FAA and Air Force are funding Livewire. A comparison of the wiring fault location capabilities of TDR, FDR, STDR and SSTDR has been published in [Furse2005a, Furse2005b, Furse2006 and Griffiths2006].

### 2.1.10. PASD

Pulse Arrested Spark Discharge [Schneider2005] – A low energy but high voltage signal is injected into wiring to induce a static discharge in areas of pin hole failures within insulation. This was developed at Sandia National Labs. It will be difficult to be qualified as to not harming active/live electronics. Astronics Corp. has licensed this technology from Sandia and is trying to commercialize it.

### 2.1.11. Partial Discharge Detection

G.E. Research [Ganesh2007] reports investigating partial discharges for 115 VAC, 28 VDC, 5 VDC and even 1 VDC. The signals captured by current sensors are analyzed with pattern recognition techniques. This work builds on the sensor development work presented in [Bulumulla2005]. Several different pattern recognition techniques have been used such as wavelet thresholding for the pattern detection [Ma2002]. The actual physical processes of dielectric breakdown involved with partial discharges have been studied in the high voltage power industry (several thousand volts) [Liu2005]. The energies involved in discharges in the power industry of course far exceed those currently found in aircraft. The work in [Imai2005] studied repeated discharges for microgaps which may be relevant to quantifying the expected energy levels involved with arcing lug connectors that the arc fault community has been studying.

### 2.1.12. Optical Current Sensors

(7/2005) – *Method for diagnosing degradation in aircraft wiring* – Optical current sensor with 0-50kHz and analyze current flow differential. ( U.S. patent #6,909,977). Typical optical sensing approaches use the phase distortion that occurs within the fiber when exposed to an electromagnetic field. Changes in phase can be used to estimate changes in electric current.

### 2.1.13. Acoustics

Two approaches to sensing the vibrations inherent to an improperly secured harness involve essentially sensing through piezo-electric transducers the accelerations of the actual harness. In one case, the small business Innovative Dynamics, Inc (www.idiny.com) place transducers to sense the vibrations at discrete points. Another approach from the University of Dayton Research Institute [Craft2007] is to string piezo wire either within or external to the wiring harness. This is essentially a long continuous accelerometer. When clamps become loose, the sensed vibration frequencies shift lower. Piezo wire, such as that from Measurement Specialties Inc. has been developed for embedded road applications such as counting vehicles.

### 2.1.14. Summary

All of the wire fault detection methods described here can be categorized as to using one of two techniques: 1. injecting an electrical signal (either directly or inductively) and then measuring reflections and/or transmissions (directly or inductively), 2. measuring externally to the harness either affects on fiber optic cable that is with the harness or acoustic emissions.

## 2.2. Active Methods for Assessing Fiber-optic Cables

New planes (e.g. Boeing 787) contain a large amount of fiber-optic cable because it can carry many communication channels on a single fiber resulting in a decrease in weight and an increase in bandwidth. This trend is expected to continue. Because diagnostic techniques commonly found in the telecommunications industry for fiber have not fully transitioned to the aircraft community, we are highlighting the methods here.

Active interrogation of fiber-optic cables typically entails injection of optical energy of known properties (pulse shape, center wavelength, polarization state, *etc.*) into the cable, and subsequent detection of the energy transmitted and reflected by the cable. The physical properties of the fiber-optic cable modify in unique ways the properties of the waveforms propagating along the cable. An understanding of this interaction is helpful in deducing the cable properties from the incident, transmitted, and reflected waveforms. If this understanding is detailed and analytical, cable properties may be estimated quantitatively; if the understanding is only qualitative, then so will be the assessment of the cable "health."

### 2.2.1. Characterization of fiber-optic cables

#### 2.2.1.1. Nominal cables

In interrogating a fiber-optic cable, one is mainly interested in assessing any damage or degradation that the cable might have experienced between inspections. Of course, the effects of damage and degradation are interwoven with the nominal response of the cable, and therefore the latter must be characterized beforehand so that it can be separated out to isolate the signatures of off-nominal behavior in the data.

The nominal behavior of a cable has two main aspects: attenuation and dispersion [Gowar1984, Agarwal1997]. Attenuation describes the exponential reduction of optical power due to absorption and scattering. These can be further categorized as being intrinsic or extrinsic to the material (*i.e.*, fused silica glass): the latter can be improved upon by refined manufacturing techniques, whereas the former constitutes an inherent property of the material that cannot be eliminated. Meanwhile, dispersion refers to the broadening of an optical pulse upon propagation. For a given fiber-optic cable, the effects of these processes can be quantified from manufacturer's data sheets, and verified in the lab prior to installation, providing a baseline assessment of a healthy cable.

*Intrinsic absorption*

Glasses used in fiber-optic cables have strong molecular absorption bands in the UV (ultraviolet) (due to electronic transitions) and in the IR (infrared) (due to vibrational transitions). The upper UV band edge is around 0.7 μm, while the lower IR band edge is around 1.6 μm.

*Intrinsic scattering*

The non-crystalline nature of glass leads to considerable molecular density fluctuations in fiber-optic cables. These random inhomogeneities act as scattering centers, diverting light from its original propagation path. The effect is the same as Rayleigh scattering in the atmosphere, and its intensity scales with the inverse-fourth power of wavelength. Its main influence is confined to visible and UV regions, and is largely negligible in the IR.

*Extrinsic attenuation*

This is due to impurities in the glass. While metal impurities have been minimized through improvements in the manufacturing process, water dissolution in glass is still a significant problem, which leads to OH radicals with vibrational bands near 1.2 μm and 1.4 μm. Also, dopants used in graded-index fibers may lead to additional scattering.

As a result of the combined effect of the above processes, the two main transparency windows of glass fibers are near 1.3 μm and 1.5 μm.

*Material dispersion*

This effect is due to the wavelength dependence of the refractive index. Whenever a pulse of finite (*i.e.*, non-zero) bandwidth is injected into a fiber-optic cable, the different wavelength components that make up the wave packet propagate at different velocities, dictated by the spectral variation of the glass index near the center wavelength of the injected pulse. As a result, the pulse broadens by an amount proportional to the cable length. (More exotic behaviors may also be seen in specialty fibers due to this effect.)

*Modal dispersion*

This effect is seen in multi-mode fibers, where the differences in the group velocities of the different modes lead to propagation delays between the modes of the incident waveform. This becomes more pronounced with increasing length of cable, until mode coupling due to “irregularities” saturates the effect. Graded-index fibers minimize this effect by optimally shaping the transverse refractive-index profile from the core to the cladding.

*Wavelength dispersion*

This effect, more noticeable in single-mode fibers due to the absence of modal dispersion, is due to the dependence of the mode structure on the ratio between the core radius of the cable and the wavelength of the incident radiation. It also leads to pulse broadening in proportion to cable length.

*Nonlinear dispersion*

In theory, the response of a medium to an applied electromagnetic field is not purely linear, and contains terms that depend on the higher powers of the field amplitude. These are usually too weak to contribute significantly and are therefore neglected, leaving only the familiar refractive-index term. However, in applications where the injected pulses are of extremely short duration, one may experience, for the same amount of total power, high enough pulse amplitudes to excite these terms. As a result, high-intensity parts of the pulse experience a different phase shift than do the low-intensity parts, altering the pulse shape. In a single-mode fiber, nonlinear dispersion may be made to cancel out the combined effects of material and waveguide dispersion, producing solitary waves (solitons) that can propagate extremely long distances without changing their shape.

*Polarization-mode dispersion*

This effect is noticeable mainly in single-mode fibers. Fiber cables can carry energy that is polarized in two orthogonal directions transverse to the cable axis. Birefringence of the cable, either due to material properties or owing to stress and deformation, leads to different propagation speeds for these two polarization components, which in turn causes pulse broadening.

#### 2.2.1.2. Off-nominal cables

Any macroscopic (geometric) or microscopic (structural) change in the properties of a fiber-optic cable will be referred to as damage or degradation, even though some types of changes (*e.g.*, bends) may be reversible. We now give a list of possible damage and degradation mechanisms; the list is necessarily incomplete, as there are many possible ways in which a fiber-optic cable can be altered.

*Deformed cross-section*

Most common is elliptic deformations. Parameters are semi-minor and semi-major axes at the point of greatest pinch, and the profile of perturbation along the cable.

*Undulating axial position*

Most common is sinusoidal. Parameters are peak deviation and period and length along the cable.

*Bends and twists*

Bends and twists are very likely to be encountered on aircraft. Parameters are curvature and torsion, and location along the cable.

*Random longitudinal perturbations*

Most common are core–cladding interface irregularities, thermodynamic fluctuations of the refractive index, micro-cracks. These are typically modeled as random processes with suitable statistical properties.

*Discontinuities and tapers*

These include connectors as well as splices and breaks. Parameters are axial and angular offset, and longitudinal gap length.

### 2.2.2. Optical time-domain reflectometry

OTDR (optical time-domain reflectometry) was first proposed in 1976 as a non-destructive technique for characterizing loss in fiber links [Barnoski1976]. Since that time, several variants (*e.g.*, correlation OTDR, photon-counting OTDR, coherent-detection OTDR) have been developed to alleviate the limitations of the original scheme. For a long time, OTDR was the only commercial tool available for the maintenance of fiber-optic communication links. Over the last decade or so, more sophisticated techniques have been making it out of the laboratory and into the commercial realm; however, the relative simplicity of OTDR is likely to sustain its widespread use into the foreseeable future.

The best-known version of OTDR involves the injection of a single pulse of light into the fiber, and the direct detection, by a photodiode, of the reflected light over time. The received trace is plotted as a function of reflected power (in dB) vs. distance along cable (in km). Since OTDR measures round-trip power loss, the trace has to be scaled by a factor of two along both axes. (This, however, is only a crude way of correcting for the round-trip effects.) Furthermore, the speed of pulse propagation has to be known accurately along the entire length of the fiber cable in order to be able to convert time (the measured axis) to distance (the desired axis).

The typical OTDR trace consists of three main feature classes:

Straight line segments – these are due to the distributed attenuation (absorption and scattering) in the cable; the (negative) slope of a segment gives the corresponding attenuation coefficient.
Steps – these are due to non-reflective defects such as bends and fusion splices; the steps are typically in the direction of diminished power, except possibly at points where two fibers with different attenuation coefficients are spliced together.
Spikes – these are due to reflective defects, such as connectors, couplers, and breaks, where an abrupt discontinuity in the light path is encountered.

Main aspects of OTDR are summarized below:

*Noise*
The fundamental obstacle in accurately measuring a cable's impulse response is the ever-present noise in the system. The sources of noise are the intensity fluctuations associated with the light source, the shot and thermal noise at the detector, and speckle noise in a multi-mode fiber, as well as any background radiation that is not shielded out of the system. The signal-to-noise ratio sets the basic limit on how accurately the reflected pulse shape can be determined and related back to the defect parameters. This limit can be somewhat alleviated by averaging multiple OTDR measurements obtained under identical conditions.

*Spatial resolution*
This refers to the instrument's ability to resolve two closely spaced defects. The spatial resolution of OTDR is determined mainly by the duration of the injected pulse and the response time of the detector, as the returned pulse shape is a convolution of these two functions with the cable's impulse response. One can improve the resolution by shortening the injected pulse duration while simultaneously broadening the detector bandwidth. However, both of these strategies lead to a noisier return signal.

*Dynamic range*
This refers to the maximum amount of loss that can be measured by the instrument, and is usually taken to be the difference between the initial reflection from the OTDR–cable connector and the noise floor of the system. The detection scheme used (direct vs. coherent) has a significant impact on the dynamic range achievable by OTDR.

*Measurement range*
This refers to the maximum length of cable over which defects can be identified. As the injected pulse propagates down the cable and back to the detector, its energy is diminished by the distributed and localized attenuation in the cable. Beyond a certain length, the signatures of defects become buried in the noise, and are therefore increasingly difficult to identify. (Clearly, the larger the dynamic range of the instrument, the longer the measurement range.)

*Dead zones*
This refers to the inability of the instrument to register a defect shortly after a strong reflective defect has been encountered. A strong return signal from a reflective defect can saturate the detector. During the time it takes for the recorded trace to return to the

correct power level, additional return signals from defects immediately downstream from the primary event cannot be captured.

*Ghosts*
Another problem that has to be contended with in OTDR is that of “ghost” reflections. If the fiber cable has multiple, highly reflective defects (*i.e.*, breaks), then the segment(s) of cable between adjacent defects will act as a cavity that traps a part of the pulse energy, and bounces it back and forth, sending out a series of echo pulses of diminishing amplitudes. As a result, the detected signal will contain ghosts generated by these multiple reflections, which can confuse the interpretation of the received trace.

*Directionality*
If the cable under study consists of several segments of fiber with different properties that were spliced together, then the measured OTDR trace will depend on which end of the fiber is used as the measurement port. In general, measurements must be made from both ends to correctly discriminate between reflective and non-reflective defects.

### 2.2.3. Optical low-coherence reflectometry

OLCR (optical low-coherence reflectometry) is based on a technique known in optics as white-light interferometry; its first use for fiber-optic cable testing was reported in 1987 [Youngquist1987].

OLCR is essentially a Michelson interferometer. Light from a low-coherence (*i.e.*, wide bandwidth $\Delta\lambda$) optical source (*e.g.*, a light-emitting diode) is split into two arms. The reference arm contains healthy fiber cable whose end facet illuminates a movable mirror; meanwhile, the measurement arm consists of the fiber being interrogated. The optical signals returning from the two arms are combined and detected by a photodiode. The reference arm contains a single reflection due to the mirror, while the measurement arm contributes reflections from all the defects in the fiber-optic cable being tested. Since the coherence length of the source is very short, the two reflected signals interfere constructively only if the position of the movable mirror at the end of the reference arm is coincident with that of a defect on the measurement arm. Constructive interference leads to an enhanced photocurrent at the detector, signaling the presence of a defect.

In typical operation, the movable mirror is scanned at a constant velocity, $v_m$, which moves the electrical signal out of the base-band and up to an intermediate frequency centered around $f_{IF} = 2v_m/\lambda$, where $\lambda$ denotes the center wavelength of radiation. This heterodyne detection scheme avoids the base-band noise in the system, and is responsible for the enhanced sensitivity of OLCR. Furthermore, since detection is coherent, the detector current is proportional to the square root of the defect reflectivity, which leads to a significant improvement in dynamic range. Since both the reference and the measurement arms contain the same type of fiber-optic cable, the effects of dispersion are also minimized in this scheme. Finally, the spatial resolution of OLCR, roughly equal to $\lambda^2/(2n\Delta\lambda)$, can easily reach a few microns, whereas the spatial resolution achievable with the best OTDR schemes is still around a few millimeters.

The issue of ghosts persists in OLCR: weak cavities formed by the various facets in the system introduce spurious interference peaks in the detector signal. Although they can be identified and dispensed with relatively easily by a human operator, an automatic means for their elimination is, of course, desirable in a commercial unit. To date, the main progress in this direction has been made by reducing the reflectivity of end facets.

An issue unique to interferometric techniques is that of polarization: propagation through an optical system (such as a fiber-optic cable) changes the polarization state of an optical beam. When two beams originating from a common source but propagated through different optical systems are combined, the resulting interference peaks can be entirely washed out if the mismatch between their polarization states is large enough. In order to prevent this, OLCR instruments use a polarization-diversity receiver involving polarizing beam-splitters and polarization controllers. This inevitably leads to a more complex hardware implementation.

The main practical shortcoming of OLCR has been the need for a movable mirror (and high-precision translation stage) in the reference arm, which limited its use for component (rather than fiber) characterization due to its short measurement range. Clever, but not necessarily elegant or fully successful, schemes have been invented to circumvent this difficulty for fiber-optic communication links. This is obviously less of a concern for short-run avionics links.

### 2.2.4. Optical frequency-domain reflectometry

OFDR (optical frequency-domain reflectometry) is at once the oldest and the newest technique on the block: while the underlying principle goes back to the development of coherent RF radar, the technology required for its commercial implementation in the optical domain has only recently become available. In addition to the many advantages of OLCR, the need for a movable mirror is replaced in OFDR with the need for a tunable laser source. There has been a great push in the communication industry over the past decade for just such a source for WDM (wave division multiplexing) transmission, and the fruits of this effort are now being reaped in other fields, including fiber-optic testing.

Under ideal conditions, a fiber-optic cable can be considered as a linear time-invariant system, and its *optical* input–output relationship can thus be written in the form [Saleh1991]

$$p_{\text{out}}(t) = \int_0^t h(t-t')\, p_{\text{in}}(t')\,\mathrm{d}t'$$

where $p_{\text{in}}$ and $p_{\text{out}}$ respectively denote the *optical* input and output waveforms, and $h(t)$ is the cable's impulse response that we wish to reconstruct. In OTDR, one attempts to achieve this reconstruction by using a narrow pulse as input. As $p_{in}(t) \to \delta(t)$, one obtains $p_{out}(t) \to h(t)$, as desired. Of course, this scheme suffers from the practical shortcomings mentioned above.

In OFDR, by contrast, one uses a highly stable, narrowband laser source, approximating an input waveform $\cos(2\pi f_c t)$. Any defects in the fiber under test modulate this waveform by simply changing its amplitude and phase, the latter in proportion to the distance to the defect. One can thus extract the complex reflectivity of a defect by mixing the returned signal with the local oscillator at the detector. The detector signal then consists of pronounced peaks at the beat frequencies proportional to the distance to the defects along the cable. As the laser frequency $f_c$ is scanned over a range $B$, a spatial resolution of $c/(2nB)$ is achieved, where $c$ is the speed of light and $n$ is the refractive index of glass.

Coherent heterodyne detection endows OFDR with the same advantages enjoyed by OLCR. Signal fading caused by depolarization is again dealt with via the use of a polarization-diversity receiver design. Measurement range of OFDR, while better than that of OLCR, is also somewhat limited, owing to the deleterious effects of phase ambiguity and phase noise over large distances.

For a long time, the tunable lasers were unavailable which hampered commercialization of OFDR [Derickson1998]. Thanks to the recent development of stably and repeatedly tunable external-cavity lasers with sufficiently large tuning ranges, this is no longer the case. Still, OFDR measurements require a stable environment in which to operate, as well as additional apparatus (*e.g.*, a gas cell) to monitor the absolute wavelength and tuning accuracy of the source.

Recently, OFDR has been used as a means for distributed sensing of the environment around a fiber-optic cable [Duncan2007]. This approach relies on the fact that each fiber-optic cable possesses a unique Rayleigh-scattering pattern that can be used as a "fingerprint." Under extreme temperature or stress conditions, the microscopic inhomogeneities inside the cable change their optical properties (*i.e.*, scattering cross-section, anisotropy, *etc.*), which can be sensed as a spectral shift in OFDR return signal.

As the tunable-laser technology matures further, OFDR can be expected to become the dominant practical tool for inspecting fiber-optic cables aboard aircraft.

### 2.2.5. Summary

The assessment of fiber optic health has two uses. The first and most studied use (in the telecommunications industry) is to detect changes in high-bandwidth communication channels that will either reduce bandwidth or cause errors or loss of transmission. The second way that fiber health assessment can be utilized is to use it as an adjunct sensor to an electrical wiring harness. This could be as simple as monitoring for inoperable fibers as an indicator of abnormal stress on the wiring harness. A more sophisticated approach would be to monitor the fibers and through inverse modeling use them to deduce harness movement.  An even more sophisticated approach is to detect small changes in phase within the fibers as a result of electric fields being emitted from the electrical wiring.  No matter the use, the basic approaches are to inject a signal and to then monitor the reflections and transmissions of that signal.  Where fiber parts company with electrical wiring is when the optical phase information can be used to either assess geometry or physical health.

## 2.3. Small Business Developments

### 2.3.1. Sensata

Sensata is considering offering an arc fault circuit interruption (AFCI) device that also contains an SSTDR unit for advanced diagnosis.  Sensata is commercially producing AFCIs.  This is work that is done in conjunction with Livewire (the source of the SSTDR technology).

### 2.3.2. MSI Sentient

MSI Sentient is marketing replacement wiring harnesses that incorporate diagnostic chips within the connector.  Livewire is also implanting chips within connectors for diagnosis via SSTDR.

### 2.3.3. Lectromec

Lectromec is in the business of chemical and physical laboratory analysis of wiring harnesses that have been pulled.  Part of their efforts with the FAA has been to identify unseen insulation faults within multi-wire harnesses as well as to perform aging assessment of dielectric materials used on wires.  One of their products that the FAA has invested in is known as the Wire Insulation Deterioration Analysis System (WIDAS).

### 2.3.4. Solers Corp.

Solers has received an DoD SBIR to develop a wavelet based “fingerprinting” system for TDR.  The approach is classical feature vector formation using a wavelet basis.  This work was done in conjunction with [Hinders2006].

### 2.3.5. System & Processes Engineering Corp. (SPEC)

SPEC is developing an Optical Health Monitoring System for wiring. The proposed system claims to permit real time, continuous monitoring of wiring at arbitrary pressures and excitation frequencies and will determine both magnitude and location of any discharge on the wire with spatial resolution of less than one foot.

### *2.3.6.* Livewire

Livewire is a spin-off from Cynthia Furse’s research lab at the University of Utah.  They are developing both smart connectors that have a SSTDR type chip within the connector, and a hand held device for signal injection and fault localization

[Furse2005a, Furse2005b, Wu2006, Sharma2007]. The hand held device actually consists of two hand held units. The first is connected onto one end of the wire harness through a typical wire harness connector. This unit injects the SSTDR signal and estimates how far down the harness the open or short is located. The second hand held unit consists of two loop antennas that measure the generated electric field and magnetic field. This second unit is designed to be used as a probe that can be run along the harness to find the fault.

### *2.3.7.* Intelligent Automation Inc. (IAI)

IAI is developing a signal injection FPGA (Field Programmable Gate Array) based handheld unit that plugs into one end of a harness with a standard connector. This unit then injects a SSTDR signal on one wire while monitoring the induced signal on a different wire. The unit multiplexes to listen and test on all wire pairs. The PI on this project is Eric VanDoorn.

## 2.4. Commercially Available Wire Testing Units

This survey distinguishes between industry led research and wire testing units that are commercially available. Though dedicated to focusing upon the research challenges, in an effort to reveal the state of practice (as opposed to the state of the art) the following two references are offered.

At the 2005 Joint Aging Aircraft Conference Kevin Howard presented [Bode2005] an evaluation of COTS (Commercial Off The Shelf) wiring diagnostic systems performed by Sandia as part of the Airworthiness Assurance NDI Validation Center (AANC). The units tested were the Cable Test MPT5000L, the CK Technologies 1175-10, the DIT-MCO 2135, Northrop Grumman's AMWIT 1000, Eclypse Internationals ESP+, Jovial Test Equipment Shortstop, Phoenix Aviation ARCMAS and 3M's 900 AST. No single COTS diagnostic system was capable of consistently detecting or localizing defects other than opens and shorts. The localization results were quite varied. Most of the units were sensitive to the entered values for propagation velocities, but these were difficult for the technicians to determine. The Navy, through its efforts to concentrate its maintenance manuals down to four volumes, has reduced the problem by having a limited set of fixed propagation velocities available to be used. NAVAIR has separately evaluated the Eclypse ESP+, 3M's 900AST and Tempo TS90/100. They also had issues with the velocity of propagation terms that are unique to every wire type, routing, test equipment and test frequencies. NAVAIR chose to reduce the accuracy in favor of usability by using 5 discrete velocities of propagation values for uncontrolled Z wire and by wire type.

## 2.5. Industrial Research Wire Fault Detection

### 2.5.1. Boeing

Boeing (Apparatus and method for monitoring electrical cable chafing via optical waveguides, US6949933, 2004) has investigated using optical waveguides to detect chafing of electrical cables. Chafing damage is preferably detected by disposing several optical waveguides about the periphery of an electrical cable such that any chafing that causes damage to the electrical cable will likely also cause damage to at least one of the optical waveguides. Multiple optical waveguides of one cable segment can be connected to multiple optical waveguides of an adjacent cable segment using only a single optical waveguide connection, while still allowing each of the optical waveguides of either cable segment to be monitored independently of each other.

### 2.5.2. Tektronix

Tektronix (Swept frequency domain reflectometry enhancement Walter D. Fields et al., Tektronix, US 5068614, 1991) has suggested the use of swept frequency domain reflectometry. The instrument for this method has an input/output terminal coupled to one end of a cable. A radio frequency at the input/output terminal is converted to an intermediate frequency using a swept local frequency. The radio frequency is derived from the swept local frequency and a variable offset frequency. A controller controls the variable offset frequency, monitoring the amplitude of the intermediate frequency. A period counter counts the intermediate frequency at a first maximum response of the intermediate frequency and further counts the offset frequency at a second maximum response of the intermediate frequency. The location of a discontinuity in the cable is calculated from the counted frequencies. Tektronix continued along that path (D. Holmbo, W. Gavett, B. Rosenow, and M. Overton, "Method of detecting and characterizing anomalies in a propagative medium", US Patent 5155439, 1992) and later added requiring the acquisition and examination of a minimum number of data points to determine the presence of an anomaly in the medium. When an anomaly is detected its characteristics, such as location, type and amount of loss are determined. The characteristics are then displayed. If the anomaly is a reflectionless loss, the region containing the anomaly is examined repetitively to determine its location and to improve the accuracy of its location measurement. With each successive level of examination, additional samples are collected within the region. The new samples are combined with the existing samples to reduce random noise in the data. Through this method the location of the anomaly is re-determined with greater accuracy.

### 2.5.3. General Electric

GE (Monitoring system and method for wiring systems Gao et al, US6930610, 2005) investigated the partial discharge (PD) phenomenon. A PD sensor is configured to monitor a component of an aircraft wiring system and to acquire a monitoring signal. This investigation was refined (Low current AC partial discharge diagnostic system for wiring diagnostics Sarkozi et al, 2006, US 7030621) by proposing a method for detecting partial discharges or arcing in wiring or cables. The system employs a high-voltage AC power source to generate a high-voltage low-current AC waveform, which is propagated through a selected wire, which in turn, produces the return signal. The return signal is processed using a signal processor and then analyzed for indications of the occurrence of a partial discharge. The method detects damage to a selected wire by inducing partial discharges in a controlled manner and detecting a return signal resulting from the discharge.

### 2.5.4. ABB

ABB (System and method for diagnosing and measuring partial discharge Chaoukat Nabih Nasrallah et al, US 6313640, 2001) has investigated a method to diagnose and measure partial discharge on-line in a power transmission system. A first wideband directional clamp-on detector detects pulses corresponding to partial discharge transmitted via a transmission line. A second wideband directional detector detects pulses corresponding to partial discharge output from at least one bushing tap of a high voltage device. The first and second pulses are nulled and then added and/or subtracted, and a diagnostic and measurement system analyzes the results. The analysis determines whether the high voltage device and/or an external source produces partial discharge, the type of discharge, and the level of discharge. For analysis of internal partial discharge, external partial discharges are rejected. The diagnostic and measurement system simultaneously analyzes multiple phases of the output of the high voltage device, while the device is energized.

### 2.5.5. CM Technologies

CM Technologies (Method and apparatus for monitoring integrity of wires or electrical cables Gregory Allan et al., US 7068042, 2006) has investigated TDR instruments for generating a pulse waveform for transmission through wire. The apparatus also includes a function generator for generating an electrical or non-electrical forcing waveform for transmission through the wire. The pulse waveform is transmitted through the wire in combination with the forcing waveform. A detector measures a change in the dissipation factor values along the wire.

### 2.5.6. Hitachi

Hitachi (Method for diagnosing an insulation deterioration of a power cable Kenichiro Soma et al., US 4980645, 1990) has looked into detecting insulation deterioration resulting from water tree in power cable insulation materials (such as a rubber or plastic insulated power cables). A current charge flowing from the power cable through a grounding conductor connected to a metal shielding layer to the ground is measured by applying AC power to the power cable. The stray current flowing from the ground to the power cable is calculated. Then, a direct current component of the charging current is detected, and an intrinsic direct current component is calculated by subtracting the stray current from the direct current component. The insulation deterioration is diagnosed in accordance with the level of the intrinsic direct current component. Hitachi (Method for diagnosing an insulation deterioration of an electric apparatus Kenichiro Soma et al, US 5276401, 1994) investigated further the charging current flows through an insulation for insulating two conductors of an electric apparatus by applying an alternate current voltage thereto. A direct current component of the charging current is detected, and is amplified by biasing a direct current voltage to the alternate current voltage. An insulation deterioration of the electric apparatus is determined by an absolute value of the amplified direct current component.

### 2.5.7. Dyden

Dyden (Method and apparatus for measuring deterioration of power cable insulation Akira Ito et al, US 5469066, 1995) investigated a system for detecting a power cable for water treeing and other forms of deterioration based on the dielectric loss of the insulation of the cable. An AC test signal is injected into the conductor of a sample of cable to be tested. The voltage drop appearing across a resistor connected to the insulation shield layer of the cable is measured by means of a lock-in amplifier. A phase shifter adds to the voltage drop a voltage signal that is 180 degrees out of phase with the reactive component of the voltage drop. The output of the lock-in amplifier is the active component of the voltage drop that is representative of the dielectric loss of the insulation of the cable. This approach permits detection of trees even if they have not spread out evenly in the power cable.

### 2.5.8. Innovative Dynamics Inc.

Innovative Dynamics Inc. (IDI) is developing a Wire Health Management System (WHMS) that provides prognostic and diagnostic tools for detecting, identifying, and locating wire faults. WHMS incorporates multiple acoustic sensors into "smart" clamps to monitor wire chafing and arcing events that account for more than 50% of wire fault incidents. The sensors can also be used to detect loose connections, temperature increases indicative of fire or other wire anomalies, fluid contamination, and connector cross-mating to cover 80 - 90% of all wire incidents. Smart components also provide the capability to mitigate unwanted wiring vibration through active noise cancellation techniques, and thus extending life of key wiring components. All can be configured to be non-intrusive fault indicators such that nothing needs to be disconnected or dismantled to conduct the inspection. The system operates continuously in-flight so that mystifying intermittent conditions can be spotted as they happen. The system can also be used for ground inspections as well.

### 2.5.9. Luna Innovations

Luna Innovations is developing a method of detection of electrical wiring interconnect system (EWIS) damage due to mechanical, thermal, electrical, and chemical mechanisms by using distributed optical fiber sensors to monitor and locate wiring damage or conditions that may lead to EWIS damage. The sensing technique is capable of temporal and spatial measurement of wiring system condition. The system is sensitive to processes that degrade the EWIS in different zones of the aircraft structure and damage events associated with maintenance activities or other sources. Both transient conditions and permanent changes in state are detected. Damage modes and conditions can be sensed without imparting damage to the optical fiber sensing element. Additionally, the EWIS condition can be compared to any previous condition. This allows aircraft operators to locate areas of significant change in the health of the EWIS that require inspection. This cumulative data is also valuable for developing zonal analysis of aging processes for use in prognostic EWIS modeling.

### 2.5.10. Killdeer Mountain Manufacturing, Inc. -

Killdeer has developed a fiber optic wiring degradation detection system and diagnostic & prognostic monitoring system. This consists of multiple optical fibers strung with the harness. Should the harness suffer pinching (e.g. clamps that are too tight, poor hatches) fiber(s) would be damaged and therefore the point of damage could be determined with the use of optical domain reflectometry.

### 2.5.11. Wavetek Wandell Goltermann

*Non-invasive digital cable test system* (8/2001, 5/2002) – Amplitude measurements made at multiple frequencies with adaptive filter with Monte Carlo simulation of various error sources. (6,278,730, 6,385,237).

### 2.5.12. Sandia Corporation

*Method and apparatus for electrical cable testing by pulse-arrested spark discharge* PASD (2/2005) (6,853,196) (PASD has been described previously).

## 2.6. National Laboratories Wire Fault Detection

Most of the efforts of the national laboratories are in the form of funding small businesses and academics to further research and development efforts in wiring fault detection. Several of these efforts have already been mentioned that in one way or another are funded by NAVAIR, Airforce, FAA or NASA. One of the largest unified efforts by the DoD (although mostly not focused upon wiring) involved Andy Hess (Navy, retired) [Hess2002, Hess 2005, Hess2006, Line2006] trying to incorporate the latest in diagnostics and prognostics into the Joint Strike Fighter program (JSF) which is under contract with Lockheed Martin for delivery of the F-35. Many efforts were funded by A. Hess but it has been difficult to make the transition from small R&D efforts to flight ready hardware and software.

NASA has a small investment in wire health detection technology. Initial efforts were focused upon the Space Shuttle wiring and TDR technology [NASA2000]. Jim Cockrell (NASA ARC) [Cockrell2005, Cockrell2006] has been a strong advocate for developing appropriate information technology for knowledge-based wire maintenance systems for the space shuttle fleet. Both of these efforts have subsequently ended with the expected retiring of the Space Shuttles. Mike Sterling at NASA KSC has been a regular participant in the wire health community meetings and has been trying to help with efforts for designing for maintainability.

The Air Force and the Navy have been heavily involved in research and development of diagnostic and prognostic efforts. The primary development efforts have been in the form of SBIRs and STTRs (Small Business Technology Transfer) as listed earlier. There are two exceptions. The first is the development of new types of wiring and insulators and the second is the development of maintenance tools and processes. DoD is investing in self-healing wiring (Robert Kauffman, UDRI) whereby chemical processes occur when exposed to water and electrical current that allow for insulation to surround areas where insulation has been damaged. Although interesting, this technology is a stopgap measure since it is still necessary to first identify where the damage occurred. Another approach is to look at alternative conductors such as coated nano-fibers [Wolf2007] that could greatly reduce weight and yet are many times stronger than conventional wiring.

NAVAIR has identified four areas of interest:

- *Wiring diagnostics* – troubleshooting and diagnostic tools for fault identification and isolation. This consists of evaluation of COTS (commercial over the shelf) units such as Eclypse ESP+, 3M 900AST and the Tempo TS90/100. They are also investing in new technologies developed by Intelligent Automation Inc. (described previously), wavelet fingerprinting TDR, embedded fiber optic sensors (Luna), SSTDR multi-sensor network and partial discharges.
- *Wire maintenance* – Repair tooling for wiring maintenance. Investing in alternate wire stripper development, cold shrink tubing for use in the field and a flameless butane heat gun/soldering iron.
- *Wire installation* – Wire install and restraint devices and methods. This work includes a trade-study on different types of wire restraints and improving routing (including how to ease 3-d visualization of routing).
- *Wire performance* – Wire construction methods and materials used in the aircraft wire system. This includes funding a wire insulation trade-study on alternative insulation, and alternative or improved conductors.

Another area that the DoD is funding is in repair and assessment of fiber optics. The next section will address the current state of the art in fiber health assessment. Fiber splice kits are currently being produced by AT&T and are being assessed and tested in operations.

FAA's Aging Aircraft program has invested in detection, prevention and analysis of electrical wiring and interconnect systems:

- *Detection* – The FAA has invested in PASD and SSTR wiring fault detection technology development.
- *Prevention* – The FAA has been leading the way for arc fault circuit interruption technology development. Flight testing is now underway with selection partners and with cooperation from the Air Force. Currently there is no plan to require the use of AFCI but the FAA has been and is very supportive of the development efforts. The FAA is also developing guidelines for EWIS separation requirements.
- *Analysis* – The FAA has been funding Lectromec to both perform advanced aging assessments on different types of wiring insulation as well detailed laboratory analysis of old harnesses from retired aircraft.

Test beds

Sandia National Laboratory has maintained the Aging Aircraft NDI Development and Demonstration Center (AANC) as part of the FAA's efforts to provide realistic tests for NDI. The Center has been assigned specific tasks in developing techniques for the nondestructive inspection of static engine parts, assessing inspection reliability (POD experiments), developing test beds for nondestructive inspection validation, maintaining a FAA library of characterized aircraft structural test specimens, and leasing a hangar to house a high flight cycle transport aircraft for use as a full scale test bed. The FAA plans to relocate the test bed from Albuquerque N.M. to the FAA's William J. Hughes Technical Center in Atlantic City N.J.

There are many other smaller test beds that have developed across the nation which for the most part are not easily accessible for experimentation. The most impressive hardware in the loop simulators that we have found have been developed (and subsequently disassembled) at Boeing during development of the 777 and the 787 [Hall1991, Lansdaal2000].

## 2.7. Current Practices

### 2.7.1. Field Tests

The current practice in the field and operations for detecting and isolating wiring faults typically involves commercially available units. Standing wave reflectometer (SWR) units such as the Eclipse ESP+ allow for reliably measuring distance to fault on a single non-branching conductor for open and short circuit faults. The ESP+ requires that the user input the velocity of propagation and the impedance for the wire type. Time-domain reflectometry (TDR) units such as the 3M 900AST also provide similar fault information and require similar user input. Digital multi-meters such as the Fluke 77 provide basic resistance, open/short, and voltage measurements. Metallic time delay reflectometers (MTDR) such as the Tektronix 1502c measure distance to open/short faults along with marginal conduction path failures. High voltage, high range ohmmeters (meggers) measure the resistance of insulation. Mis-wires are identified by testing end-to-end conductivity (resistance).

### 2.7.2. S-Parameters

Microwave engineers typically employ the use of scattering matrices containing terms referred to as S-parameters [Pozar1998]. S-parameters are used when the network is linear, in other words when in the small signal domain the S-parameters are not a function of the magnitude of the input signal. A typical two wire transmission line can be thought of as a 2-port network with an input port consisting of the input end of the two wires and an output port consisting of the other end of the two wires. Consider an N-port network where $V_n^+$ is the amplitude of the incident voltage waveform on port n, and $V_n^-$ is the amplitude of the reflected voltage from port n. The scattering matrix [**S**] is defined relative to these incident and reflected waves as:

$$\begin{bmatrix} V_1^- \\ V_2^- \\ \vdots \\ V_N^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1N} \\ S_{21} & & & \vdots \\ S_{N1} & \cdots & & S_{NN} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \\ \vdots \\ V_N^+ \end{bmatrix}$$

where $S_{ij} = \left.\frac{V_i^-}{V_j^+}\right|_{V_k^+ = 0 \text{ for } k \neq j}$. Thus $S_{ij}$ is found by driving port *j* with an incident wave of voltage $V_j^+$, and measuring the reflected wave of amplitude $V_i^-$ coming out of port *i*. Note that analytically S terms are complex values of magnitude and phase.

For the case of a two wire transmission line, $S_{11}$ is the reflection coefficient seen at the input when the output is terminated in a matched load. $S_{21}$ is found by applying an incident wave at port *1*, $V_1^+$, and measuring the out coming wave at port *2*, $V_2^-$. This is the transmission coefficient from port *1* to port *2*.

## 2.8. Requirements Definition & Metrics

Performance metrics for health management fall into three broad categories: Detection, Isolation and Prognosis [Roemer2005]. This survey is focused upon detection and isolation for wire and connector faults. For both detection and isolation it is important to consider:

- Confidence
- Receiver Operator Characteristic (ROC) analysis of false alarm rates
- Sensitivity to external variations
- Stability
- Repeatability
- Accuracy of characterization/severity

The process of defining requirements for wire health management is still in an early stage of development. As research and development progresses for different approaches, a basic understanding of what is possible begins to emerge and subsequently becomes incorporated into requirements. Obviously the operators (both commercial and military) desire a fault locating device that is capable of reliably determining shorts and opens within a few centimeters. More significantly, the goal of assessing insulation damage prior to a short or open condition needs significant analysis. But there is a fundamental need for several different types of requirements to be formed:

1. Requirement for localization and characterization of open & short circuit faults
2. Requirement for procurement of field operable devices
3. Requirement for intermittent fault localization
4. Requirement for characterizing chafing
5. Requirement for characterizing intermittent connectors

**Point #2. Quantitative Assessment - *There needs to be careful quantitative assessment of real-world effects that are typically ignored in the laboratory and appear randomly during field tests. For example, the effects of varying humidity and vibration on the performance of wire fault detection schemes based upon electrical signal injection has not been substantially investigated in the literature.***

Real world effects such as humidity and vibration can wreak havoc on electrically based interrogation systems. The effects of these real world variations may have a significant impact on the achievable performance of an electrical signal interrogation system and correspondingly will affect requirements. Some requirements may be impractical or prove to be too difficult to obtain with current technology.

There is the need for mapping from requirements to specifications and then eventually to technology development. Current electrical interrogation developments for wire fault detection tend to develop with an unfortunate common pattern:

1. A preliminary laboratory study involving very clean conditions with single wires.
2. Demonstration of preliminary results and the initiation of acquiring additional funding, sometimes in the form of a Phase 1 SBIR grant.
3. Follow on developments lead to more rigorous testing but without funding for analytical analysis and without rigorous requirements definition.

There is a lack of understanding in the community as to “how good is good enough” and “how good can we get” with respect to fault diagnosis using electrical or optical signatures. This is intimately connected with practical issues such as performance metrics and false alarm rates. In the past on-board diagnostic systems have had a terrible record for costing more then was saved. For example, in [Bain2000] it is documented that built-in-tests (BIT) caused wasted (CND) maintenance of the order of 85,639 maintenance man hours and 25,881 hours unnecessary aircraft downtime. This issue has plagued the F/A-18E/F and the V-22 Osprey [Westervelt2006].

It is possible to categorize the testing and development cycles into three classes:

1. initial laboratory developments
2. fixed test-stand tests
3. flight tests

The first phase has the least uniformity amongst developments surveyed, is the least expensive to conduct, and should be but is typically not the most informative before performing more expensive tests. The second phase typically involves testing on a grounded aircraft that is specifically made available for such purposes (such as the FAA’s testing facility). The third phase is the most expensive but also the most revealing about the effects of real-world conditions such as humidity and vibration. Typically, the third phase is associated with either directed (or earmarked) funds or Phase II SBIRs (if government aircraft). Effort is needed in helping to define the testing requirements and the specific implementation standards necessary for testing in the first phase that could reduce surprises learned in the later stages. A large missing piece of the testing and validation stage is a simulation-based analysis of the expected fault types including realistic noise sources, geometric and dielectric variations as well as environmental factors such as humidity and vibration.  This leads us to our fourth point in the survey:

**Point #3. Testing & requirements guidance - Every wire health management project, whether associated with a smaller academic effort, a small business innovative development, large industry/system integrator efforts or flight operations should be evaluated in the same way.  This should include a three prong effort utilizing simulation, theoretical characterization and laboratory data collection involving realistic environmental factors such as humidity and vibration.**

## 2.9. Mathematical Physics Modeling & Simulation

### 2.9.1. The utility of mathematical physics

To better understand the impact of applying knowledge of the underlying physics to retrieving more information out of the observed data, we provide a simple example.  On the left side of Figure 5, a limited number of noisy observations are presented.  Without any additional information about the experiment, it is very difficult to see a pattern. One's first inclination might be to try to see if there is a trend within the dataset by fitting a line or curve by minimizing least square error.  If the observation noise is independent and Gaussian then this results in a maximum likelihood operation.  If a line does not seem to fit well then higher order functions may be tried to fit the data.  The cases of fitting a line, a quadratic curve and a cubic spline are shown on the right in Figure 5.

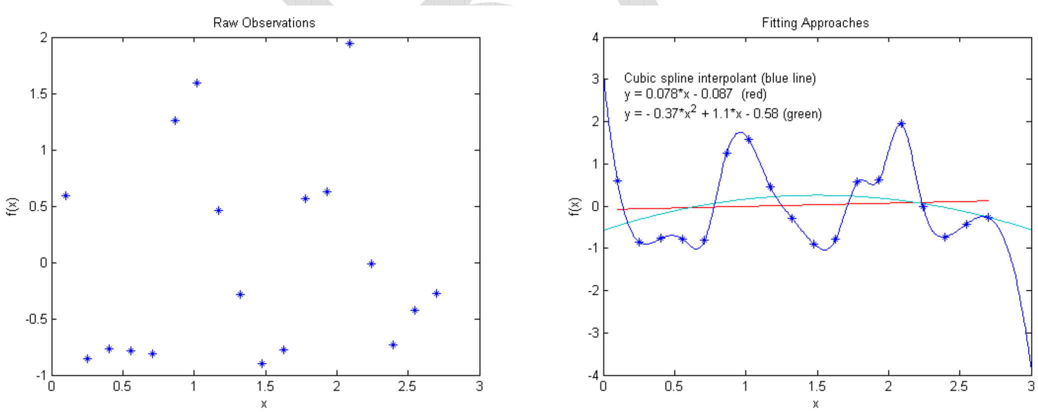


**Figure 5. Noisy observations on the left, various fitting approaches on the right: line, quadratic and cubic spline.**

Now if instead we are allowed to incorporate the underlying physics of the experimental setting, it may be possible to achieve much better results.  For example, if we knew that the experiment involves measuring an oscillator with a fixed frequency, we would fit a sinusoid on the same data by developing a parametric mathematical model of the physics (e.g. find the appropriate frequency of a sinusoid). The result of this is shown on the left in Figure 6. If there is still doubt, we reveal the many sample case from the same system on the right side of Figure 6.

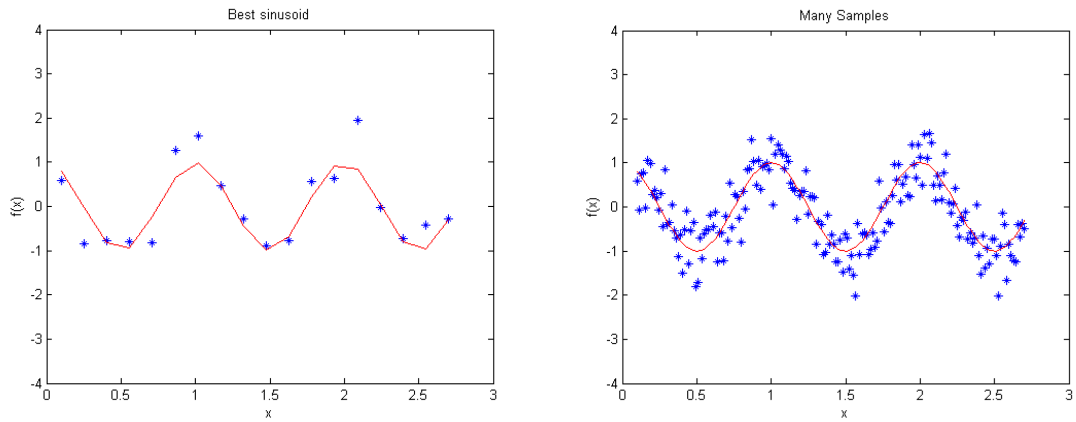


**Figure 6. Sinusoidal fit to data, few sample case on left, many sample case on right.**

### 2.9.2. Uniform Transmission Lines

Most TDR applications in use to date are intended for detection of discrete discontinuities such as open and short circuits. For such situations, each discrete change of the dielectric causes a reflected wave. Conventional techniques fail when there are multiple or continuously varying discontinuities. Standard techniques ignore the multiple reflections and the superposition of reflections which motivates us to examine the theory behind parameter retrieval using non-uniform transmission line theory. Before diving into the mathematics of non-uniform transmission line theory, it is important to understand the simpler case of uniform transmission lines.

Starting with Maxwell's equations:

$$\nabla \times E = -j\omega\mu H$$

and

$$\nabla \times H = -j\omega\varepsilon E$$

where *E* is the electric field phasor, *H* is the magnetic field phasor, $\mu$ is the magnetic permeability, $\varepsilon$ is the permittivity, $\omega$ represents frequency and $j = \sqrt{-1}$.
We can derive the theory for uniform transmission lines [Cheng89].

Assuming the simplest case of a parallel plate transmission line with lossless conductors and with an induced *y*-polarized TEM (transverse electromagnetic) wave propagating in the +z direction as shown in Figure 7.

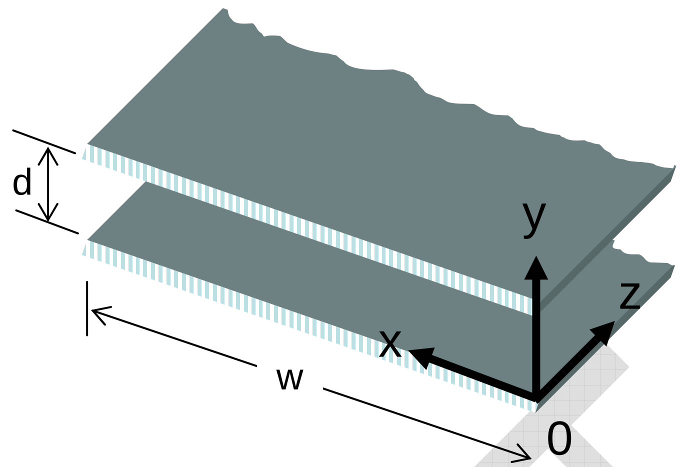


**Figure 7.** Parallel-plate transmission line.

The TEM wave assumption requires that $E_x = E_z = H_y = 0$. Thus we can rewrite Maxwell's equations:

$\frac{dE_y}{dz} = j\omega\mu H_x$ and $\frac{dH_x}{dz} = j\omega\varepsilon E_y$

If we integrate the first expression over the separation distance *d*:

$-\frac{dV(z)}{dz} = j\omega\left(\mu\frac{d}{w}\right)\left(J_{su}(z)w\right)$ where $J_{su}$ is the surface current on the conducting plane.

Integrating the second expression over the width *w*:

$-\frac{dI(z)}{dz} = j\omega\left(\varepsilon\frac{w}{d}\right)\left(-E_y(z)d\right)$, we get the inductance per unit length in Henries per meter: $L = \mu\frac{d}{w}$ and the capacitance per unit length in Farads per meter: $C = \varepsilon\frac{w}{d}$. Combining these two differential expressions yields the *transmission line equations:*

$\frac{d^2V(z)}{dz^2} = -\omega^2 LCV(z)$ and $\frac{d^2I(z)}{dz^2} = -\omega^2 LCI(z)$.

Now we can relax our initial assumptions and let the conductors have resistance and the dielectric medium have a nonvanishing loss tangent. The conductance between the two conductors separated by a dielectric medium having permittivity of $\varepsilon$ and a conductivity of $\sigma_d$ is $G = \sigma_d\frac{w}{d}$. The resistance can be expressed as [Cheng89]:

$R = \frac{1}{w}\sqrt{\frac{\omega\mu_c}{\sigma_c}}$.

Thus the electromagnetic characteristics of a uniform transmission line are functions of four parameters {L, C, R, G} as shown in Figure 8:

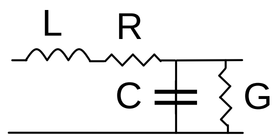


**Figure 8.** A lumped parameter L, C, R, G network represents how inductance, resistance, capacitance and shunt conductance can be used to represent a uniform transmission line.

The standard transmission line models make the following assumptions that can be relaxed when addressed in the non-uniform formulation:

1. *Insulation is uniform and without variation or flaws* - This assumption is addressed in the non-uniform model either by having multiple lumped terms or by having continuously varying parameters. This is critical if we want to be able to detect and isolate flaws due to chafing.
2. *Defining parameters do not change along wire* - Parameters such as propagation velocity and permittivity can vary greatly when there is a severe flaw in the insulation of the wiring. A non-uniform transmission line formulation allows for these variables to be functions of position.
3. *Geometry is straight* (critically bad assumption for high frequency analysis) - This assumption is addressed in the non-uniform model by allowing for the attenuation and L, C, R, G parameters to also account for variations in bend radius (or wiggles). Several groups have worked on specifying the lumped parameters dependent upon bend radius [Lam1976, Lam1977, nakamura1995, Ye2002], but none of these have incorporated this into a fully continuous invertible model. Tkachenko et al. [Tkachenko2005] developed a mixed potential integral equation for a thin curved wire intended for forward simulation not necessarily parameter retrieval. Typically for the lumped parameter case, the bend radius translates into additional L and C terms. FDTD simulations can clearly show energy radiating from bends in the microwave frequency range (which in most practical applications of TDR is limited to below 20 GHz).
4. *Infinitely long* - Transmission lines are infinitely long so that multiple reflections do not occur. This assumption must be mitigated when updating model parameters from laboratory data and simulation data.
5. *Transmission lines are suspended by devices that have dielectric properties significantly different from the wire's insulation* - Haase2003 points out that these attachment points should also be modeled to enable a capable assessment.

### 2.9.3. Non-uniform Transmission Lines

The mathematics for modeling propagating waveforms on uniform transmission lines is well understood and easily derived from Maxwell's equations [Cheng1989, Jackson1998]. The mathematical formulation used to model varying properties of wiring insulation (e.g. permittivity) as a function of position (fault location) is known as non-uniform transmission line theory. The non-uniformity in permittivity will cause multiple reflections when an incident waveform is introduced as shown in Figure 9. There are many ways to categorize approaches to this problem. We have chosen to distinguish between what we would characterize as discrete from continuous approaches.

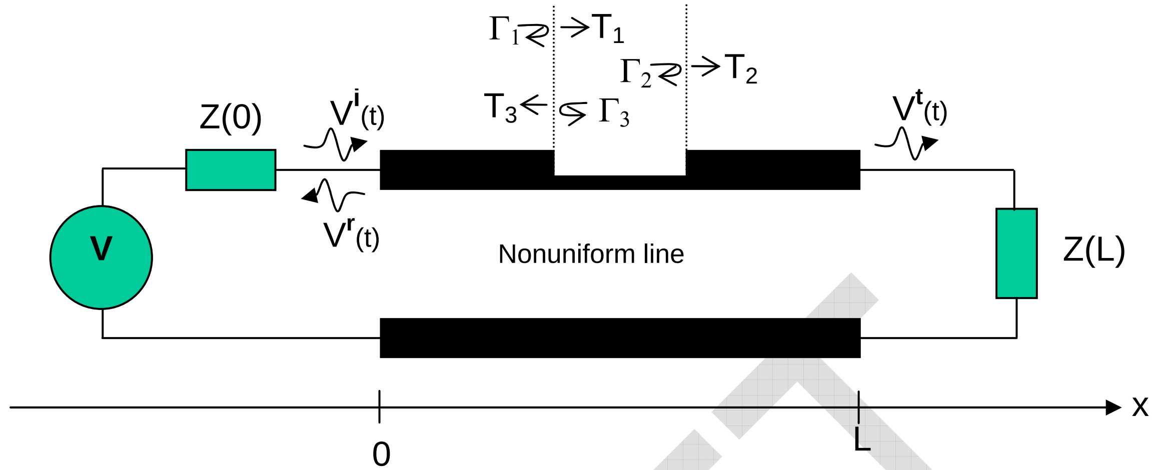


**Figure 9.** Multiple reflections occur when an incident voltage is present on one end and there is a variation in the insulation thickness (permittivity). The reflections Γ and also the transmitted voltages T can be used to characterize and localize faults in the insulation.

The basic physics underlying all non-uniform transmission lines is that there are four spatially varying components: an inductive term (represented by L), a series resistance (represented by R), a shunt capacitance between the conductors (represented by C) and a shunt conductance between the conductors (represented by G).

$$-\frac{\partial V(x,t)}{\partial x} = L(x)\frac{\partial I(x,t)}{\partial t} + R(x)I(x,t)$$

$$-\frac{\partial I(x,t)}{\partial x} = C(x)\frac{\partial V(x,t)}{\partial t} + G(x)V(x,t)$$

### 2.9.4. Discrete Methods (TLM)

Discrete methods rely upon a lumped parameter model as shown in Figure 10.

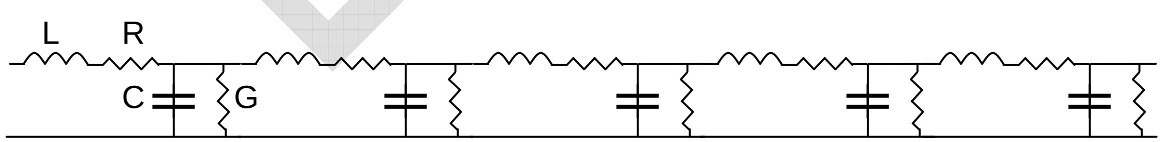


**Figure 10.** Lumped parameter transmission line with five stages.

The advantage of this type of formulation is that the solution can be put in terms of linear algebra for a frequency-based solution (e.g. using a Laplace transform). The distinct disadvantage for assessing unknown faults in wiring is that the number of discrete circuits is unknown, but if assumed known can be cause for the wrong solution to be concluded. The size of the smallest insulation flaw is constrained by the number of lumped terms. There are a number of different approaches to formulating recursive update equations that take advantage of discrete layers [Bechhoefer2005, Hsue1997, Sekine2005 and Yonemoto2003]. Some of these approaches involve making simplifying assumptions, for example, assuming a lossless network that only consists of reactive impedance.

### 2.9.5. Continuous Methods & Model Inversion

Rather than assume a discrete number of lumped networks or "layers", the continuous version tries to model the unknown parameters as functions (not necessarily differentiable) of space (location on wire). The formulation of continuous models tends to rely upon Green's functions [Jackson1998]. The difficulty is then to retrieve the correct values for the unknown impedance and velocity terms from the measured voltage reflections and transmissions. This retrieval process is known as model inversion.

The essential idea behind model inversion is the process of fitting a model that has variables (parameters) that can be changed to "best" fit the observed data, where best is defined by some cost functional. In the simplest case of fitting a line to data points, the cost functional is typically the least squares error. This is also known as maximum likelihood when the measurement noise process is thought to have a Gaussian distribution. In a truer Bayesian approach to model inversion, the cost function is to maximize the posterior probability.

There are many ways in which to formulate Maxwell's equations to perform inversion for the transmission line problem. It is also true that there are usually many real-world variables that are not taken into account by these models such as vibration, movement and humidity. Some of these are difficult issues that need to be addressed through appropriate research. There are several mathematical formulations for dielectrics that are worth mentioning.

### 2.9.6. Dielectric Polarization Formulation

The insulation on wiring can be characterized by how the permittivity of this dielectric changes along the wire. The electric susceptibility of a dielectric is a measure of how easily a material polarizes and determines the permittivity. In non-wiring tasks, it is often necessary to characterize a dielectric material via the reflections that occur from electromagnetic wave interrogation. This is similar to characterizing the state of wiring insulation based upon the reflections measured by TDR and other similar methods. In order to understand this interrogation process, it is important to understand the various mathematical formulations of susceptibility. Three common types dielectric models are the Debye, Lorentz and Drude media [Taflove2005].

The Debye media's susceptibility function for the $p^{th}$ pole as a function of frequency $\omega$ :

$$\chi_p(\omega) = \frac{\varepsilon_{s,p} - \varepsilon_{\infty,p}}{1 + j\omega\tau_p} \equiv \frac{\Delta\varepsilon_p}{1 + j\omega\tau_p}$$

where $\varepsilon_{s,p}$ is the static permittivity, $\varepsilon_{i,p}$ is the high-frequency permittivity and $\tau_p$ is the propagation time.

Taking the inverse Fourier transform of this reveals the time-domain response:

$$\chi_p(t) = \frac{\Delta\varepsilon_p}{\tau_p} e^{-t/\tau_p} U(t)$$

where *U(t)* is the unit step.

If the Debye medium has multiple relaxation poles, the relative permittivity may be expressed as:

$$\varepsilon(\omega) = \varepsilon_\infty + \sum_{p=1}^{P} \frac{\Delta\varepsilon_p}{1 + j\omega\tau_p}$$

A Lorentz media has one or more pairs of complex-conjugate poles. For a Lorentz medium characterized by a single pole pair, we have:

$$\chi_p(\omega) = \frac{\Delta\varepsilon_p \omega_p^2}{\omega_p^2 + 2j\omega\delta_p - \omega^2}$$

where $\delta$ is the damping coefficient and $\omega$ is the frequency of the pole pair.
The time-domain version is an exponentially decaying sinusoid:

$$\chi_p(t) = \frac{\Delta\varepsilon_p \omega_p^2}{\sqrt{\omega_p^2 - \delta_p^2}} e^{-\delta_p t} \sin\left(t\sqrt{\omega_p^2 - \delta_p^2}\right) U(t)$$

For a Lorentz media having P pole pairs:

$$\varepsilon(\omega) = \varepsilon_\infty + \sum_{p=1}^{P} \frac{\Delta\varepsilon_p \omega_p^2}{\omega_p^2 + 2j\omega\delta_p - \omega^2}$$

The Drude model has become widely used for treating electromagnetic wave interactions with metals using a dispersive formulation at optical wavelengths. A single-pole Drude medium is expressed:

$$\chi(\omega) = -\frac{\omega_p^2}{\omega^2 - j\omega/\tau_p}$$

The real-valued time-domain susceptibility function yields:

$$\chi_p(t) = \omega_p^2 \tau_p \left(1 - e^{-t/\tau}\right) U(t)$$

For a Drude media having P poles:

$$\varepsilon(\omega) = \varepsilon_\infty - \sum_{p=1}^{P} \frac{\omega_p^2}{\omega^2 - j\omega/\tau_p}$$

At any point in a linear dispersive medium, the time-domain electric flux density *D(t)* is related to the electric field intensity *E(t)* by:

$$D(t) = \varepsilon_0 \varepsilon_\infty E(t) + \varepsilon_0 \int_{\tau=0}^{t} E(t-\tau)\chi(\tau)d\tau$$

Banks et. al. [Banks2001, Banks2005a, Banks2005b and Banks2006] have developed a mathematical framework for allowing the relaxation parameter $\tau$ to be drawn from a probabilistic distribution. The parameters of these distributions are then determined via a least squares procedure based upon observed reflections. Banks discusses different media models and different distribution possibilities.

### 2.9.7. Compact Green's functions with Split Waves

In the late 1990's, Lundstedt and Strom [Lundstedt1996 and Lundstedt1997] published a method for retrieving the LCRG parameters of a non-uniform transmission line using measured reflection and transmission voltages in the time domain. This work built upon earlier work on compact representations and split wave approaches to modeling Maxwell's equations [Lundstedt1994, He1991, He1992a, He1992b, He1993a, He1993b, He1996, Kristensson1986a, Kristensson1986b, Kristensson1987, Kristensson1989, Norgren1996 and Weston1988].

The fundamental principle behind Lundstedt & Strom's work uses Weston's [Weston1988] split wave approach whereby the voltage at any point along the non-uniform line (see Figure 9) can be represented as having a right going wave and a left going wave:

$$V(x,t) = V^+(x,t) + V^-(x,t)$$

This split wave representation can then take advantage of He's [He1992a, He1992b, He1993a He1993b and He1996] compact Green's function formulation:

$$V^+(x, t+\tau(0,x)) = a^+(x)V^t(t) + G^{c+}(x,t) * V^t(t)$$

$$V^-(x, t+\tau(0,x)) = a^-(x)V^t(t-2\tau(x,l)) + G^{c-}(x,t) * V^t(t)$$

where the *a(x)*'s represent the spatially varying attenuation (right/left is +/-), and $G^{c+}(x,t)$ and $G^{c-}(x,t)$ are the compact Green's function which are convolved with the transmitted voltage waveform $V^t(t)$. The propagation time is represented by:

$$\tau(0,x) = \int_0^x \frac{1}{c(x)} dx$$

where *c(x)* represents the spatially varying propagation velocity.

Using the appropriate boundary conditions the incident and reflected voltages can be represented as:

$$V^i(t) = a^+(0)V^t(t) + G^{c+}(0,t) * V^t(t)$$

$$V^r(t) = a^-(0)V^t(t-2\tau(0,l)) + G^{c-}(0,t) * V^t(t)$$

The compact Green's functions depend upon four spatially varying unknowns:

$$\{Z(x), c(x), R(x), G(x)\} \Leftrightarrow \{G^{c+}(x,t), G^{c-}(x,t), a^{+}(x), a^{-}(x)\}$$

where $Z(x) = \sqrt{\frac{L(x)}{C(x)}}$ is the reactive impedance.

For the problem of determining the faults associated with chaffing of the insulation, we don't really care about any of these terms. Instead, we need to form yet another mapping that relates the spatially varying impedance, propagation velocity, resistance and shunt conductance to the permeability, permittivity, conductance of the dielectric and resistance:

$$\{Z(x), c(x), R(x), G(x)\} \Leftrightarrow \{\mu(x), \varepsilon(x), \sigma_d(x), R(x)\}$$

At the end of the day, we want to retrieve the spatially varying permittivity and the dielectric conductance as measurements of the health of the wiring insulation.

Most if not all of the variables within these models are actually stochastic by nature, although they have been represented as deterministic values. For example, there are variations in the real-world that are not represented. This only makes the model inversion more difficult to achieve reliably. Small variations in the harness position or ground level changes in the adjacent wires can cause changes in the mutual inductive coupling between the wires. Inversion of models with random variables has been studied and developed over
many years within the Bayesian statistics community.

**Point #4. Understanding electromagnetics** ***Understanding how the electromagnetic wave propagation changes within wiring with damaged insulation is fundamental to developing signal injection and measuring devices for fault detection and prognosis.***

We have had discussions with both Livewire and Intelligent Automation Inc. and their principle investigators. Of particular interest to us was the extent of simulation and modeling they have each done in order to validate and verify optimal performance of their diagnostic systems before implementation. Unfortunately due to the way SBIRs are funded, the deep theoretical work necessary to understand how good is good enough tends to come after development. Although both researchers were indeed eager to pursue simulating various injection schemes with respect to fault types, neither had done so prior to this writing. The exception to this is the publication by Furse's group [Griffiths2006]. Although this paper is pursuing the relevant questions, the simulation techniques are frequency based rather than time-based and the critique is done sans model and thus cannot retrieve fault parameters.

### 2.9.8. Modeling of optical waveform propagation

The propagation of electromagnetic energy along a fiber cable is governed by Maxwell's equations. The application of Maxwell's theory to a cylindrical dielectric rod leads to the identification of a rich mode structure [Marcuse1974, Snyder1983]. Specifically, the waveform inside the cable can be written as a superposition of eigenmodes that are bound (*i.e.*, guided), leaky, or radiating (*i.e.*, evanescent). Bound modes are characterized by a discrete spectrum of real-valued eigenvalues. Leaky modes are similar to bound modes but with imaginary components in their eigenvalues, which lead to their gradual coupling out of the waveguide over long distances. Radiation modes are characterized by a continuous spectrum of imaginary-valued eigenvalues, and are therefore not propagated beyond a distance of a few wavelengths. (The intrinsic attenuation in the cable introduces its own loss through an imaginary contribution to the eigenvalues.)

The general expression for a propagating electric field inside a fiber-optic waveguide thus takes the form:

$$E(\vec{r},t) = \sum_i \left[a_i(z)\vec{e}_i(x,y)\exp(j\beta_i z) + a_{-i}(z)\vec{e}_{-i}(x,y)\exp(-j\beta_i z)\right]$$

$$+\sum_k \int_0^\infty \left\{a_k(z,q)\vec{e}_k(x,y,q)\exp[j\beta(q)z] + a_{-k}(z,q)\vec{e}_{-k}(x,y,q)\exp[-j\beta(q)z]\right\}dq$$

and includes both forward- and backward-traveling terms. The amplitudes *a*, the transverse polarization-mode profiles $\vec{e}$ , and the propagation constants $\beta$ incorporate into this expression the nominal characteristics of the cable listed above.

The modeling of off-nominal cable characteristics can be handled in two different ways. Small perturbations can be modeled as a coupling mechanism between modes (the coupled-mode theory), and their effects can therefore be studied within the same analytical framework. Large perturbations, on the other hand, require the introduction of "local" modes (*i.e.*, a different set of *a*'s, **e**'s, and $\beta$'s) that provide a more accurate description of the field structure near the damage site. This new eigen-system is then matched to the normal modes at a convenient (usually fictitious) boundary between healthy and damaged segments of the cable. These local modes allow the introduction of a parametric model of damage into the waveform propagation formalism, which paves the way for the application of Bayesian model inversion techniques toward inferring the state of the cable from reflection and transmission measurements.

### 2.9.9. Bayesian Approaches to Model Inversion

Over the last decade, Bayesian methods have been increasingly gaining popularity in application to diagnosis and prognosis because they provide quantifiable measure of uncertainty on the estimates. The Bayesian philosophy has a long history and yet is fairly simple and succinctly explained in a small paperback by Sivia and Skilling [Sivia2006]. The essential idea is to assign a quantifiable measure of certainty of belief to all possible variables. The application of this method to electrical health assessment [Sheppard2005, Chiodo2006, Barrett1994, and Khalak2005] is in its infancy.

The Bayesian formula is quite simple:

$$p(\text{model} \mid \text{data}) = \frac{p(\text{data} \mid \text{model})\, p(\text{model})}{\sum p(\text{data} \mid \text{model})\, p(\text{model})}$$

Where the terms represent:
*p(*data **|** model) – ***likelihood*** of seeing the observed data given that our physics model has the parameters as specified (*Forward problem*). In microwave design problems, it is possible to use advanced computational techniques (see next section) to simulate this in the time-domain with finite difference approximations. In practice, when it is necessary to perform real-time inference, these forward model simulations are replaced with a reduced order computation for a faster response.

*p*(model) – ***prior*** information, this encapsulates such information as the type of wire insulation, geometry of wire and insulation, valid parameter ranges such as the minimum and maximum velocities of propagation.

*p*(model **|** data) – ***posterior*** that allows us to find the physical system traits (such as faults, depth of chafing fault…) (*Inverse Problem).*

With respect to finding faults in electrical wiring, the posterior would be $p(\varepsilon(x)|I\ldots)$ the probability of the permittivity having some value along any particular location represented as *x*. The simplest case would be to have two distributions for permittivity, one with mean centered at the mean value of permittivity for the nominal cable, and the other for the particular fault of interest. This of course can be easily extended to continuously varying faults through the use of more sophisticated posterior distributions. One example of this might be a mixture of Gaussians model. Non-parametric distributions are also possible such as infinite mixture Dirichlet process models [Gosh2003].

Although initial formulations for retrieving L, C, R, and G have been published [Lundestedt1997, Lundestedt1996 and Lundstedt1994], very little analytical work has occurred in quantifying the appropriate distributions that represent noise from all other terms. Research is needed to quantify:

- Development of appropriate noise models for realistic environments (e.g. varying humidity and vibrations).
- Development of the trade-off between false alarms and detectability (how little of a fault can we detect).
- Development of rapid retrieval algorithms for near-real time assessments.
- Comparison of parameter retrieval from data obtained by commercial simulators and laboratory collection.

### 2.9.10. Computational Electromagnetics Modeling Packages

To acquire enough data in an efficient and cost effective manner necessary for the development of a forward (likelihood) mathematical model, it is necessary to employ a realistic simulator. To that end, we have included in this survey the availability and efficacy of current software offerings as they relate to modeling injected and measured high frequency signal propagation, with an emphasis on applications in a multi-wire harnesses found inside aircraft.

The substantial increase in desktop processing power and reduction in memory costs have led to a large-scale increase in computational electromagnetic (CEM) software packages in the past decade. Problem domains and sizes previously relegated to supercomputers may now be routinely solved using desktop workstations in standalone or multi-client configurations, spurring substantial academic exploration and the production of commercial and open source software packages. Many excellent books are available on the subject of computational electromagnetics. Some well referenced books include [Taflove2005] for all things Finite Difference Time Domain (FDTD), Sadiku covers many different simulation techniques (Sadiku2001]. The classical reference for applying the Finite Element Method to model Maxwell's equations is [Jin2002].

#### 2.9.10.1. Modeling Steps and Software Components

Typically, all electromagnetic modeling packages must perform a series of distinct and critical steps to approach each modeling problem. The general steps to follow are 1) define the geometry of the problem, choosing the degree of physical accuracy with which each of the components in the model will be represented, 2) assign physical properties to the objects within the model from a materials database, 3) generate a mesh which is a representation of the geometry and contains the physical properties in each element, 4) apply an electromagnetic solver algorithm which is appropriate form the problem domain, 5) allow post processing of the results and 6) present the results to the user.

The notable differentiation between commercial CEM modeling packages and Open Source CEM modeling packages is the integration of the different software components in the CEM modeling process. In general, commercial CEM packages provide an all-in-one solution with tightly integrated components, often relying on proprietary optimization methods that flow between the meshing and numerical solver to achieve optimal performance. Open source CEM packages tend to provide only the core solver code itself, and either recommend third party packages to perform the other functions in the modeling process, or leave the user to find their own. It should be noted that though lacking the graphical interface universally found in commercial products, open source software is nominally available to perform each of the required steps in a CEM modeling project as stated above.

### 2.9.10.2. Computational Electromagnetic Modeling Solver Techniques

At the core of any CEM model is the solver used to calculate the propagation of electromagnetic waves. Multiple computational electromagnetic solver techniques exist, and no one particular method is considered the best for every problem. The most appropriate method depends to a great extent on the particular problem that is to be analyzed, especially when dealing with simulation of measurement equipment and specific signal detection. Analytical methods are very good at analyzing problems with a high degree of symmetry and are computationally less intensive than other alternatives, but tend to provide more global insights into a problem. To achieve an accurate evaluation of realistic electromagnetic problems and their real world geometries generally requires a numerical approach.

*Method of Moments (MoM)*

The method of moments (MoM) or boundary element method (BEM) is a method of solving CEM models by formulating them as boundary integral problems. MoM techniques require only that the boundary of interest be meshed into discrete segments, not the entire volume of the problem domain. In general, moment method techniques are most suitable for analyzing unbounded radiation problems and homogeneous dielectrics whose solution on the surface of the object is of interest. They are not well suited to the analysis of complex inhomogeneous geometries, nor are they well suited for calculating true volume solutions. Though widely available commercially, these form of solvers are not appropriate for application to modeling signal transmission in a wire bundle.

*Finite Element Modeling (FEM)*

Finite element techniques require the volume of the model domain to be entirely meshed, instead of just the surface features as in surface integral methods. The advantage is that each mesh element may have unique properties from all other mesh elements, providing complete flexibility in defining the underlying problem domain. In general, finite element methods are best suited for modeling complex, inhomogeneous models. The computation requirements are significantly greater than those for MoM techniques, but FEM techniques are completely suited to modeling complex wire structures.



### 2.9.10.3. Finite Difference Time Domain (FDTD)

Finite difference time domain (FDTD) techniques require that the entire volume of the modeling space to be divided into a mesh representation in which the electric and magnetic fields are calculated. Normally, this mesh must be uniform, so that the mesh density is determined by the smallest detail of the configuration and memory requirements can grow quite large for small, complex structures. FDTD techniques work in the time domain, which makes them suited to transient analysis problems. In particular the simulation of TDR equipment is a natural implementation in an FDTD simulation. Like the finite element method, FDTD methods are very good at modeling complex inhomogeneous configurations, though restriction on the shape of the mesh cell can create larger memory requirements than FEM.

#### 2.9.10.4. Available CEM Modeling Packages

A vast array of computational electromagnetic packages are available that address some, if not all, of the modeling components required in a CEM package ranging from geometry specification through user output. In the following synopsis, a small set of software packages were highlighted based on relevant feature sets, availability of modules to perform each of the critical modeling steps, ease of use, cost, and in the case of open source, how widely adopted and supported the code base seemed to be. A comprehensive table of all surveyed packages is found in Table 1.

The criteria set for recommending a modeling package are based on the numerical solver at the core of the electromagnetic computation, the ancillary software packages that create ease of use, tight integration, and rapid deployment for use with other analytical packages, and the level of support available for the specific package. In particular, modules for the specification and/or import of geometry, materials definition, meshing, and post processing capabilities were seen as the most important components to cross-compare.

*Highlighted Commercial FDTD Packages*

Two commercial packages that utilize the FDTD solver method are highlighted. Each package contains a complete suite of tools for specifying and encoding the geometry with an optimized meshing function to maximize computational speed and/or accuracy. These tools are tightly integrated and tested with each other, providing a higher level of confidence in the overall modeling process than what could be achieved from using multiple third party packages for each step in the process.

**MICROWAVE STUDIO** – Computer Simulations Technology (http://www.cst.com)

- Description - Full Wave 3-D EM Solver for high frequency signals. Exceptionally user friendly interfaces and graphically oriented for creating geometry, meshing, and post processing. Rapid learning curve for creation of simple models, but extensive capabilities for arbitrarily complex problems. Tutorials available for modeling a TDR system attached to a wire. Multi-processor capable.
- Geometry – internal CAD, or import of SAT, STEP, IGES, STL, Pro/E, CATIA, Inventor, VDA-FS, CoventorWare, Voxel Import file formats.
- Materials – library included
- Meshing – Adaptive mesh generator integrated with each solver to optimize processing
- Solvers – Multiple (Transient Solver Module, Frequency Domain Solver Module, Eigenmode Solver, Multilevel Mulitpole Method).
- Post processing – Extensive visualization, probe placement, field extraction
- Additional Features – Pre-built TDR feature, programmable control from Matlab, Excel

- Availability – In use at Langley, available for free trial at Ames

**XFDTD – REMCOM** (http://www.remcom.com)

- Description - 3D full-wave Finite Difference Time Domain software, including Conformal FDTD. Very mature package, used extensively for modeling EM interaction with the human body. GUI for geometry construction, probe placement. Multi-processor capable.
- Geometry – Internal CAD tools, plus import of SAT, DXF, STL, STEP, IGES, PRO/e, CATIA, Inventor
- Materials – Materials library included
- Meshing – Adaptive meshing with optimization functions
- Solvers – C/FDTD
- Post Processing – Limited interactive display, export to bitmap and movie sequence
- Additional Features – Scriptable for extended runs
- Availability – 30 day trial

*Highlighted Commercial FEM Packages*

Two commercial packages that utilize an FEM solver are highlighted. Both packages contain integrated modules for specifying and encoding the geometry of the models, and extensive materials libraries to define the physical characteristics of each component. Depending on selected modules, both are capable of simultaneous multi-physics calculations, accounting for not only the EM characteristics but also thermal and acoustic effects if desired. The addition of multi-physics capabilities provides a more extensive modeling platform than the FDTD solvers, but requires substantially greater computing resources to implement. The primary highlight within this group is Comsol Multiphysic Engine due largely to cost, and its tight integration with Matlab for extended analysis and system integration in the scope of the large wire integrity project.

**Comsol Multiphysics Engine** (http://www.comsol.com)

- 2D and 3D Static, low-frequency (quasi-static), and full-wave field solvers based on the finite element method. Multiphysics engine supports EM, thermal and acoustic effects. Multiprocessor capable
- Geometry – Internal CAD, Import of STL, VRML, DXF, GDS, NASTRAN, STEP, IGES, SAT, Parasolids, CATIA, Inventor, Pro/E, VDA-FS
- Materials – extensive materials library
- Meshing – Adaptive Mesh generation and optimization
- Solver – Simultaneous FEM using all physics modalities
- Post Processing – extensive graphical outputs, custom numerical reports.
- Additional Features - Seamless interface and export of models to MATLAB/Simulink. Graphical placement of EM field probes.

**Maxwell 3D – Ansoft** (http://www.ansoft.com/products/em/max3d/index.cfm)

- Full-Wave, general 3D EM solver using finite element method. Very mature package, widely used in industry for all forms of generalized EM modeling purposes. Multiprocessor capable.
- Geometry – Internal CAD, Plus import of SAT, DXF, STEP, IGES, Pro/E
- Materials – included library
- Meshing – Adaptive, optimized mesher
- Solver – FEM
- Post Processing – Extensive interactive and graphical output. Numerical report generation.
- Additional Features – Multiphysics capable with add-on modules

*Highlighted Commercial Miscellaneous Solvers*

Outside the traditional full wave EM solvers, packages designed specifically to model the electrical activity of wire harnesses have been developed. Though significantly less flexible than generalized EM packages, modeling wire harnesses directly as LC models provides a rapid computational path towards examining simple signal transmission. One commercial package specifically addresses the modeling of wire harnesses found in aircraft, boats and automobiles, and could provide a low-cost low computational resource solution to implementing a simulated TDR system.

**MHARNESS** – EMA (http://www.electromagneticapplications.com)

- Full Wave EM solver, wire harness simulator using FDTD methods. MHARNESS designed specifically for wire harness simulation. Single processor.
- Geometry - Allows wire bundles to be specified with each wire having its own conductive properties, insulation, and surrounding material.
- Materials – Specification of conductive properties, insulation, and surrounding insulation material
- Meshing – LC segmentation, no true meshing
- Solvers – Time domain, frequency domain derived.
- Post Processing - No graphical interface, restricted specifically to harness simulation.
- Availability – no trial available

*Highlighted Open Source FDTD Packages*

Open source software packages are abundant, springing largely from academic labs in many universities. The general characteristic of these packages is that they are tailored to the author's particular area of interest, and have marginal support outside the efforts of a user community. Consequently the learning rate can be slow, and initial implementation can take significant amounts of time. Another issue to be aware of is the general lack of integrated support programs, requiring other 3rd party software to perform such functions as geometry specification, materials definition, meshing, and post processing of the data.  The primary benefit of such packages is that they are open source, so that the system is fully customizable and expandable and the project demands.  There is also no cost associated with obtaining and implementing the software, provided the available community support is sufficient to provide a tutorial or learning tool.  Due to the plethora of available packages, only a single highlight is put forth due to its maturity and sizeable user base.

**MEEP – MIT (http://ab-initio.mit.edu/wiki/index.php/Meep)**

- FDTD Full-Wave solver with support for 1d/2d/3d cylindrical geometry specification, dispersive and non-linear media, and distributed-parallel implementation. Written primarily in C++, but requires FORTRAN support for some aspects.  Seems to be the most widely used and developed open-source FDTD system.  Fairly steep learning curve to move beyond toy problem definitions.
- Geometry – Internal specification of geometry.
- Materials – Moderate definition of dispersive and non-linear media, primarily aimed at optics.  Moderately supported definition of metal.
- Meshing – moderate mesh support on analytic geometry specification.
- Solver – FDTD.
- Post Processing – Output to HDF format, no built in capabilities.  HDF utilities available to visualize and parse output files.
- Additional Features – support is moderate and unofficial.  Software stability is not as strong as commercial product due to academic nature of package.  Scripting is supported for extended batch processing.
- Availability – download at site.  Linux only.

*Open Source FEM Packages*

Implementations of efficient open source FEM packages, with regards to computing resources, are more difficult to determine than FDTD packages.  Two packages are highlighted as potential code bases that would be suitable for an extended development project of an FEM simulator.  The first candidate, EMSolve, is not open source to the public, but the source code is available to NASA and other government agencies free of charge.  Similar to other open source packages, EMSolve requires all 3rd party tools to define and encode geometry and post-process the data.  The package is considered a very powerful and accurate simulator, and is used by Lawrence Livermore National Laboratory contractors for modeling projects for the DoE and the DoD.  The authors of EMSolve have mentioned that extensive training would be required to implement their code, and that training is not freely available.  The second candidate, EMAP5, does not have the high profile of EMSolve, but is suitable as a code base (per the authors statements) in the construction of an in-house FEM system.  Included in the package is a hybrid FEM/MoM solver technique that is unique to this package.

**EMSolve - LLNL**
(http://www.llnl.gov/CASC/sc2001_fliers/EMSolve/EMSolve01.html)

- Extensive RF solver that can be used on single or multiprocessor system, written primarily in Python and C++. 2D and 3D full-wave solvers. Targeted primarily at supercomputer implementations. Code is sparsely documented, and no tutorial exists. Manager of EMSolve code base feels strongly that several weeks of hired consultant time would be necessary to implement a problem in EMSolve. Code is freely available to NASA but consultation fees would apply.
- Geometry – no support.
- Materials – no support
- Meshing – no support
- Solver – FEM
- Post Processing – no support.

**EMAP5 – University of Missouri-Rolla (http://www.emclab.umr.edu/emap5)**

- EMAP5 is a full-wave electromagnetic field solver that combines the method of moments (MOM) with a vector finite element method (VFEM). It employs the finite element method (FEM) to analyze a dielectric volume, and employs the method of moments (MoM) to solve for currents on the surface of (or external to) this volume. The two methods are coupled through the fields on the dielectric surface.
- Geometry – only suited for simple geometries.
- Materials – minimal library
- Meshing – no support
- Solver - Hybrid FEM/MoM solver.
- Post Processing – no support
- Availability - download

**Table 1. CEM Full-Wave Solver Packages**

| S/W Name | Company | Method | Domain | Availability | URL |
|---|---|---|---|---|---|
| Ansys Multiphysics | Ansys | FEM | Time & Frequency | Commercial | http://www.ansys.com/products/multiphysics.asp |
| Amaze3D | Field Precision | FEM | Frequency | Commercial | http://fieldp.com |
| Comsol Multiphysics w/RF module | COMSOL | FEM | Frequency | Commercial | http://www.comsol.com/products/rf/ |
| CONCEPT II | TUHH | MoM | Frequency | Academic | http://www.tet.tu-harburg.de/en_EN/en_concept_general.php |
| Concerto | Vector Fields | FEM, MoM, C/FDTD | Time & Freq | Commercial | http://vectorfields.com |
| EMA3D | EMA | FDTD | Time | Commercial | http://www.electromagneticapplications.com |
| EMDS | Agilent | FEM, ? | Frequency | Commercial | http://eesof.tm.agilent.com/products/emds_main.html |
| EMMCAP | | Curved MoM | Frequency | Academic | http://www.herrara.unt.edu.ar/nnlineales/emmcap/ |

| | | | | | |
|---|---|---|---|---|---|
| EMSight | Applied Wave Research | MoM | Frequency | Commercial | http://www.appwave.com |
| EMSolve/EIGER | LLNL | FEM,MoM hybrid | Time & Freq | MPI only, poor PC | http://www.llnl.gov/CASC/sc2001_fliers/EMSolve/EMSolve01.html |
| EZ-FDTD | EMS-Plus | FDTD | Time & Freq | Commercial | http://www.ems-plus.com |
| FEKO | Electromagnetic Software | MoM/UTD | Frequency | Commercial | http://www.emss.co.za |
| Fidelity | Zeland | FDTD | Time | Commercial | http://www.zeland.com |
| FullWave | Infolytica | FEM | Frequency | Commercial | http://www.infolytica.qc.ca |
| GEMACS | GEMACS | MoM/UTD | Time & Freq | Commercial | http://www.gemacs.com |
| HFSS | Ansoft | FEM | Frequency | Commercial | http://www.ansoft.com/ |
| HFWorks | ElectroMagneticWorks | FEM | Frequency | Commercial | http://www.electromagneticworks.com |
| IE3D | Bay Technology | Full Wave Integrator | Time & Freq | Commercial | http://www.bay-technology.com |
| Maxwell 3D | Ansoft | FEM | Frequency | Commercial | |
| MEEP | MIT | FDTD | Time & Fre | Academic | |
| Mefisto 3d | Faustus Corp | TLM | Time | Academic | http://www.faustcorp.com |
| Mharness | EMA | FDTD | Time | | http://www.electromagneticapplications.com |
| Microwave Studio | CST | FDTD, multiple | Time & Frequency | Commercial | http://www.cst.com |
| MSC Nastran | MSC | FEM | Frequency | Commercial | http://www.mscsoftware.com/ |
| NEC-2 | LLNL | MoM | Frequency | Free | |
| NEC-4 | LLNL | MoM | Frequency | Limited | |
| PAM-CEM/CRIPTE | ESI-Group | FDTD | Time | Commercial | http://esi-group.com |
| pulseFDTD | CEMTACH | FDTD | Time | Free | |
| QW-3D | QWED | CFDTD | Time | Commercial | http://www.qwed.com.pl/ |
| RADAR-FDTD | Carsten | FDTD | Time | Free | http://carsten.welcomes-you.com/radarfdtd/ |
| SEMCAD | Speag | C/FDTD | Time & Freq | Commercial | http://www.speag.com |
| toyFDTD | CEMTACH | FDTD | Time | Free | |
| Wipl-D | Artech House | MoM | Frequency | Commercial | http://www.artechhouse.com |
| XFDTD | Remcom | FDTD | Time & Freq | Commercial | http://www.remcominc.com |

### 2.9.10.5. Forward Modeling

The time-domain software simulation packages can be used to see the effects that different types of insulation faults have on the propagation of the electrical signals. This *forward model* is an inherent part of assessing the degree of faults from laboratory and field data observations.

Current development efforts are focused upon using injected signals to identify wiring damaged from reflected and inductively sensed waveforms. These efforts depend upon the electromagnetic wave propagation changing with respect to particular types of insulation faults. To truly assess the potential of the techniques and not just the particular implementations it is necessary to understand how defects in insulation and other environmental factors (such as vibration and humidity, branching networks, etc.) affect the electromagnetic wave propagation. All three elements: 1. simulation, 2. data collection and 3. modeling and model inversion need to be taken together in order to adequately impact the wire fault detection problem. This leads us to our final point:

**Point #5. Simulation, data collection, modeling & model inversion**
***Critical analyses need to be comprised of three basic elements: 1. simulation, 2. data collection and 3. theoretical modeling and model inversion. Critical analyses must be model based. Small reflection signals buried inside of noisy time-domain data may be extremely useful if they can be pulled out. This process of signal extraction is referred to as model inversion. Without a comprehensive model, it is extremely difficult to analytically assess how well the inversion can characterize and classify wiring faults.***

The process of using simulation, data collection and model inversion is depicted below in Figure 11. There are many ways in which the process could be configured. In this depiction the computationally expensive electromagnetic simulations have been performed off-line in order to create a comprehensive parameter distribution set and in order to establish appropriate parameter priors.

The first step in the monitoring process is to inject an electrical signal into the harness. This is followed by measuring the reflections and transmissions. These observations are then used to retrieve fault parameters combining the mathematical model with the off-line simulation data. If the estimated level of uncertainty is below a certain threshold then the fault assessment may issue an appropriate alert. If the uncertainty is too high, then the parameter estimates need to continue. This continuation of signal injection may result in better performance should the injected electrical signal be varied in response to the expected fault type.

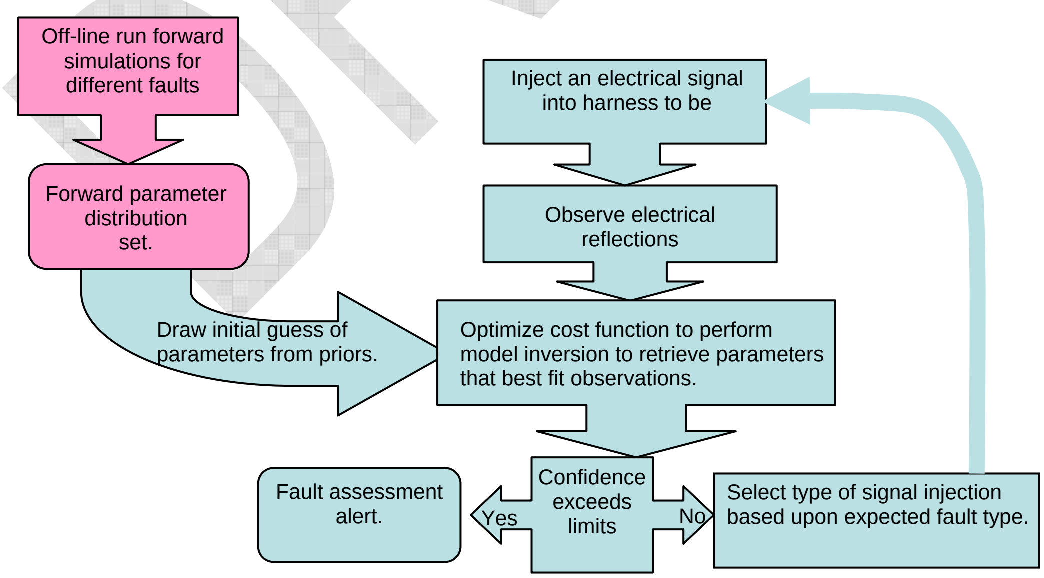


**Figure 11.** A flow diagram combines the forward model simulations with data observations, model inversion processes and on-line modification of signal injection.

# 3. Conclusions and Recommendations

## 3.1. National research and development portfolio gap assessment

Electrical problems of aircraft associated with wire chafing and connector faults account for well over half of all electrical problems. As the average age of fleets increases electrical problems are expected to get worse. Currently, the two most challenging problems are detecting the chafing of insulation before shorts occur, and the identification of intermittent continuity as might be found within faulty connectors (e.g. pin pushback and corrosion). For the most part, the aging wiring community has concluded that a rigorous approach to the problem is too difficult and therefore ad hoc approaches are funded with the hope of developing a workable solution. After investigating the research and development efforts of academia, industry and the national laboratories we have come to the following recommendations:

1. A library of realistic wiring fault signatures needs to be developed that is open to a broad community.
2. Mathematical formulations need to be developed that incorporate real-world variations (such as vibration and humidity) appropriate for intermittent faults that can be used in simulations prior to expensive hardware development and flight tests. This includes developing model inversion software routines that are tuned to assess the requirements of fault diagnosis along with the efficacy of signal injection approaches.
3. Testing and requirements guidance needs to be developed to assist in the development and selection of wire health management technologies based upon practical results that can be derived from simulation and laboratory data.
4. Electromagnetic formulations need to be developed and assessed with respect to parameter retrieval for chafed wiring as might be found with a non-uniform transmission line formulation.
5. The efforts of simulation developers, model inversion developers, and hardware developers need to be combined within a single effort to take full advantage of the possibility of retrieving small signals buried within reflections and in determining the best signal injection strategies.

## 3.2. The Under-studied Problems

### 3.2.1. Intermittent faults/shorts

The majority of effort to date for wire fault detection systems has been focused upon faults that are static; either full open or short circuits or chaffed insulation. Enormous time and energy is currently spent in operations on faults that appear during the flight and then cannot be duplicated on the ground. The community needs to define intermittent challenge problems that incorporate intermittency.

### 3.2.2. Intermittent Connectors/Corroded Connectors

The intermittent connector problem is a greatly under-reported and under-studied problem in aviation.  The intermittent connectors that we refer to in this section are the type that screw and lock together, not the lug terminals that are being addressed by the arc fault community.

Maintenance procedures require that connectors be disengaged and reengaged.  This eventually can cause pins to push back within the connector so that only partial contact is established.  This partial contact may check out fine on the ground but can cause intermittent behavior during flight and thus is very difficult to track down.  The intermittent connector issue is partially mitigated through the use of hysteresis algorithms within the LRUs (line replaceable units).

Another contributor to adverse connector performance is corrosion.  This is particularly troublesome for marine operators such as the Coast Guard’s helicopter fleet.  Several mitigating strategies are currently being employed such as installing dehumidifiers within hangers and using anti-corrosion compounds such as self leveling green.  Unfortunately, very little research has gone into detecting invisible corrosion internal to a connector.  One approach being investigated by Robert Kauffman at UDRI is to place inductive coils before and after a connector so as to induce and measure a type of TDR pulse.  The idea is that the TDR reflections will vary based upon the amount of corrosion.

## 3.3. Addressing the gap: Research Addressing the Points

The accumulation of the information within this survey has occurred over a short period of time from many different sources.  Every effort was made to be as inclusive as possible and to honestly seek out technical gaps without any preconceived ideas.  That being said, it is our intention that the survey becomes a living document with additions and modifications made as new information becomes available.

During the process of collecting information, it became readily apparent that the information required to understand wire chafing developments and requirements within the U.S is fragmented and the required data and models are at best difficult to obtain.  During the course of this survey we have highlighted five points:

**Point #1. Fault Physics Library** ***The broad failure categories cannot be easily mapped to the physics of degradation of wiring insulation and the corresponding electromagnetic characteristics. A physics-based fault library would be of great benefit to the community, especially one that contains the electromagnetic signatures of different types of dielectric damage.  Primary fault types that should be included are chaffing, partially connected and/or corroded connectors, and intermittent signal conduction associated with breaking or shorting events.***

In many communities the availability of datasets for which academics and their students can have access has resulted in a boon of research. Current development efforts in the U.S. make the fault synthesis and data collection process inherent to funded development efforts. This results in the data collected being considered as part of the inventor's intellectual property. Although the taxpayers' money has been used to spur these developments, the data is rarely made available to anyone else (even government labs). This then causes other funded inventors (typically with SBIR or STTR funding) to repeat the fault synthesis and data collection necessary to advance the field. It would be of great benefit to the entire community if the government were to establish an electrical fault signature database that was open to all to pursue.

**Point #2. Quantitative Assessment** - ***There needs to be careful quantitative assessment of real-world effects that are typically ignored in the laboratory and appear randomly during field tests. For example, the effects of varying humidity and vibration on the performance of wire fault detection schemes based upon electrical signal injection has not been substantially investigated in the literature.***

It is extremely rare that performance results obtained in the laboratory equal those obtained in the field and during operation. Typically this is seen as necessary in the dirty real-world environment. Unfortunately, much of the gross error could be mitigated before doing expensive field trials if the primary sources of error were identified and studied. For the wire fault detection problem we know many of the sources of error which warrant further attention but which are typically ignored or vastly under-developed. For example, we know that the effects of varying vibration, humidity and multi-wire geometry affect greatly the classical signal injection techniques. With the appropriate experimental setup and with the proper mathematical framework these sources of errors can be modeled and mitigated. Without doing this it is impossible to quantify how good is good enough when testing diagnosis and prognosis developments.

**Point #3. Testing & requirements guidance - Every wire health management project, whether associated with a smaller academic effort, a small business innovative development, large industry/system integrator efforts or flight operations should be evaluated in the same way. This should include a three prong effort utilizing simulation, theoretical characterization and laboratory data collection involving realistic environmental factors such as humidity and vibration.**

It is possible to categorize the testing and development cycles into three classes:

1. initial laboratory developments
2. fixed test-stand tests
3. flight tests

The first phase has the least uniformity amongst developments surveyed, is the least expensive to conduct, and should be but typically is not the most informative before performing more expensive tests. The second phase typically involves testing on a grounded aircraft that is specifically made available for such purposes such as the FAA's testing facility. The third phase is the most expensive but also the most revealing about the effects of real-world conditions such as humidity and vibration. Typically the third phase is associated with either directed (or earmarked) funds or Phase II SBIRs (if government aircraft) and is the most expensive. Effort is needed in helping to define the testing requirements and the specific implementation standards necessary for testing in the first phase that could reduce surprises learned in the later stages.

**Point #4. Understanding electromagnetics** ***Understanding how the electromagnetic wave propagation changes within wiring with damaged insulation is fundamental to developing signal injection and measuring devices for fault detection and prognosis.***

The leading wire chafing detection efforts in the United States have devoted minimal effort to simulating the best type of signal to inject even though the success of the technology development efforts depends upon understanding electromagnetic wave propagation. Essentially the principle investigators that we have spoken with are interested in conducting these types of studies but have been unable to secure funding to do so. Since most of the funding in wire fault detection comes in the form of SBIRs (or STTRs), the development cycle is fast paced and leaves little time (or money) for the research necessary to ensure that the development directions are optimized.

The FAA has also funded modeling efforts through the work of excited dielectrics [Van Alstine2005]. Unfortunately, the approach pursed was lacking in modeling all of the unknowns by reducing to just modeling capacitance and therefore was not continued.

**Point #5 Simulation, data collection, modeling & model inversion**
***Critical analyses need to be comprised of three basic elements: 1. simulation, 2. data collection and 3. theoretical modeling and model inversion. Critical analyses must be model based. Small reflection signals buried inside of noisy time-domain data may be extremely useful if they can be pulled out. This process of signal extraction is referred to as model inversion. Without a comprehensive model, it is extremely difficult to analytically assess how well the inversion can characterize and classify wiring faults.***

Several papers by Lundstedt [Lundsted1997, Lundstedt1996 and Lundsted1994] have developed a rigorous approach to retrieving the spatially varying L, C, R and G parameters of a non-uniform transmission line. This work or ideas similar to it need to be explored further and incorporated into an inversion system that actively injects signals to both detect faults and monitor fault progression. Currently none of the development efforts that are focused upon developing hardware for wiring fault detection use any form of quantifiable parameter retrieval.

The five points raised by this survey are meant to highlight areas that we have concluded to be gaps in the nation’s portfolio. Obviously the wire and connector fault detection and prognosis problem is difficult and each agency is doing the best that it can with the resources given. It is encouraging to see the level of open communication between the agencies that are engaged in fault detection development. The gaps presented in this survey are of a fundamental nature that if addressed, could have a positive impact on the entire community. The points raised are not without controversy. Fundamentally, open access to relevant data sets would prove fruitful in encouraging academia to wrestle with this challenging problem. There are aspects, especially electromagnetic modeling, which has a down side. In particular, electromagnetic simulations are computationally very expensive and are typically not representative of even clean laboratory conditions. Once known, this issue can be mitigated using *a three prong philosophy* behind every development effort:

1. Collect data in the laboratory using environmentally realistic conditions
2. Develop a thorough theoretical accounting for all aspects of the problem including undesirable noise sources while keeping in mind that model order reduction may be necessary in order to produce timely results.
3. Perform simulations that are modified to more accurately represent real-world conditions.

Thus this summary is advocating collecting realistic data, providing this data to the community, developing the appropriate theoretical approach, using simulations and data collection for development and eventually leading to requirements definition for all aspects of the wiring fault detection problem.

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# 5. Definition of Acronyms

| | |
|---|---|
| AANC | Airworthiness Assurance NDI Validation Center |
| AFI | Arc fault interrupt |
| AFCI | Arc fault circuit interrupt |
| ATSRAC | Aging Transport Systems Rulemaking Advisory Committee |
| BEM | Boundary Element Method |
| BIT | Built-in-Tests |
| CEM | Computational Electromagnetic |
| CND | Cannot Duplicate |
| COTS | Commercial Off The Shelf |
| DoD | Department of Defense |
| DoE | Department of Energy |
| EM | Electromagnetic |
| FAA | Federal Aviation Administration |
| FDR | Frequency Domain Reflectometry |
| FDTD | Finite Difference Time Domain |
| FEM | Finite Element Method |
| FPGA | Field Programmable Gate Array |
| IR | Infrared |
| LRU | Line Replaceable Unit |
| MCR | Multi-carrier Reflectometry |
| MET | Micro Energy Tool |
| MoM | Method of Moments |
| MTDR | Metallic Time Delay Reflectometer |
| NAVAIR | Naval Systems Air Command |
| NDE | Non-Destructive Evaluation |
| NDI | Non-Destructive Investigation/Interrogation |
| NDR | Noise Domain Reflectometry |
| NTSB | National Transportation Safety Board |
| OFDR | Optical frequency domain reflectometry |
| OLCR | Optical low-coherence reflectometry |
| OTDR | Optical Time-Domain Reflectometry |
| PASD | Pulse Arrested Spark Discharge |
| ROC | Receiver Operating Characteristic |
| RTOK | Retests OK |
| SBIR | Small Business Innovative Research contract |
| SSTDR | Spread spectrum time Domain Reflectometry |
| STDR | Sequence Time Domain Reflectometry |
| STTR | Small business Technology Transfer contract |
| SWR | Standing Wave Reflectometry |
| TDR | Time Domain Reflectometry |
| TEM | Transverse Electromagnetic |
| UDRI | University of Dayton Research Institute |
| UV | Ultraviolet |
| WDM | Wave Division Multiplexing |

# 6. Definition of Symbols

| | |
|---|---|
| $a^+(t)$ | Attenuation factor for right going wave. |
| $a^-(t)$ | Attenuation factor for left going wave. |
| $a(z)$ or $a(q,z)$ | Optical amplitudes. |
| $\beta$ | Optical propagation constants. |
| c(z) | Propagation velocity as a function of location. |
| $C$ or $C(z)$ | Capacitance. |
| $\chi(\omega)$ | Susceptibility function as a function of frequency. |
| $D(t)$ | Electric flux density. |
| $\delta$ | Damping factor in dielectric model. |
| $\varepsilon$ | Electric permittivity. |
| $\varepsilon_\infty$ | Electric permittivity for high frequency. |
| $\varepsilon_s$ | Electric permittivity for static frequency (d.c.). |
| $\vec{e}$ | Transverse polarization-mode profiles. |
| $E$ | Electric field phasor. |
| $G$ | Shunt conductance. |
| $G^{c+}(x,t)$ | Compact Green's function for right going waves. |
| $G^{c-}(x,t)$ | Compact Green's function for left going waves. |
| $\Gamma_i$ | $i^{th}$ reflection. |
| $H$ | Magnetic field phasor. |
| $h(t)$ | Optical impulse response. |
| $I(z)$ | Current as a function of location. |
| $I(z,t)$ or $I(x,t)$ | Current as a function of space (location) and time. |
| $J$ | Current density. |
| $j$ | Imaginary number, square of negative 1. |
| $L$ or $L(z)$ | Inductance. |
| $\mu$ | Magnetic permeability. |
| $\mu c$ | Magnetic permeability for conductor. |
| $p_{in}$ and $p_{out}$ | Optical signal input and output. |
| $\sigma_d$ | Conductance for dielectric. |
| $\sigma_c$ | Conductance for conductor. |
| $S_{ij}$ | S-parameter, driving port $j$ with an incident wave of voltage and measuring the reflected wave amplitude. |
| $\tau(0,x)$ | Time of to propagate from location 0 to $x$. |
| $U(t)$ | Unit step function. |
| $V(z)$ | Voltage as a function of location along wire. |
| $V^+(t)$ | Right going voltage waveform. |
| $V^-(t)$ | Left going voltage waveform. |
| $V^i(t)$ | Incident voltage. |
| $V^r(t)$ | Reflected voltage as a function of time. |
| $V^t(t)$ | Transmitted voltage as a function of time. |
| $V(x,t)$ | Voltage as a function of space (location) and time. |
| $v_m$ | Scanning velocity of moveable mirror. |
| $\omega$ | Frequency. |
| $Z(x)$ | Impedance = $\sqrt{L(x)}/\sqrt{C(x)}$ |